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CLIMATIC PROBABILITIES OF THE VERTICAL DISTRIBUTION OF CLOUD CO--ETC(U)
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The probability model of areal coverage of weather conditions that was published in the Journal of Applied Meteorology (1979) is applied to extend the usefulness of climatic records of station sky cover (tenths) and ceiling height (meters) to the estimation of cloud presence at any level in the atmosphere or within any layer. Specifically, estimates are made of: (a) the average cloud cover as a function of the vertical distance above the ground, (b) the average amount of cloud presence, in layers or at individual levels, and (c) the

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20. Abstract (Continued)

probability distribution of cloud cover, from clear to overcast, at any level or in any layer between two levels.

Preface

This investigation on cloud cover originated a few years ago when the Environmental Technical Applications Center, United States Air Force (ETAC) asked AFGL to contribute to the task of simulating the atmospheric environment in tactical air/land operations. It has become increasingly desirable to continue development of a method, or methods, to find the probability of a cloud-free line of sight between two points when both points are aloft or when one point is at the ground and the other aloft. That is, there is a requirement to estimate the probabilities of cloud decks enveloping levels or layers of the atmosphere, partially, fully or not at all. It was quickly recognized that such estimates will have to be made for locations where historical data do not exist.

One workable solution is modeling the phenomena and the climatic frequencies. "Model B," as developed and described in both an AFGL report and in a journal article, is applied to provide a climatology of cloud cover. In the course of this application, a further development was found necessary to incorporate an additional parameter for the vertical distribution of clouds. In the development I was very ably assisted by a colleague, Capt Edward Geisler, who is responsible for the final form and solution (Eq. 11) for the parameter designated as α. Many discussions with my Branch Chief, Donald Grantham, my former colleague Iver Lund, and reviewers Allen Cole and Arthur Kantor, have been most helpful in improving the content of the paper.

Contents

Illustrations

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Climatic Probabilities of The Vertical Distribution of Cloud Cover

1. INTRODUCTION

Climatological tables normally provide statistical information on total sky cover and on ceiling heights, regardless of the origin, dynamics, shape or the type of the clouds. The total sky cover, as seen by a ground observer, is usually given in tenths, from clear (0/10) to overcast (10/10), without reference to the level of the clouds. The ceiling is defined as the base of the lowest opaque cloud deck that covers 6/10 or more of the sky dome. In the United States Air Force the Environmental Technical Applications Center (ETAC) has standardized the tabulations into "Revised Uniform Summaries of Surface Weather Observations," known by the acronym "RUSSWO," in which the frequency distributions of ceiling heights are combined with the frequency distributions of visibilities in matrixes, with marginal frequencies for both. Other tables give the frequency distributions of sky cover and additionally the mean sky cover, in tenths.

Useful as the standard information may be, more is often needed. On many occasions, it would be useful to know the frequencies of clouds in layers, and particularly for the likelihood of a cloud-free line of sight (CFLOS), for example, between a vehicle and its target.

This report is aimed at modeling the climatology of cloud cover that will provide the probability of a horizontal CFLOS at a given upper level, or the probability

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of a vertical CFLOS through a given layer of the atmosphere. The emphasis is on modeling, as observations are not easily summarized to provide such climatology directly. The modeling is based on the RUSSWO tables, and does not make use of other observational techniques or platforms such as aircraft, radar or satellite pictures. To be sure, these tools have been effective, as in day-to-day nephanalysis My colleagues in AFGL and ETAC have collected line-of-sight observations from both military and commercial flights over much of the world, in some seven years during which special observations were requested and were cooperatively supplied. They have presented the resulting estimates of probabilities of CFLOS for Germany (1975),[1] the USSR (1976),[2] the USA (1977),[3] Europe (1978),[4] and North Africa and the Middle East (1979),[5] from the ground up through the atmosphere. For Columbia, Missouri, estimates have been made of CFLOS from the ground to heights in the atmosphere ranging from 100 ft to 30,000 ft.[6,7] Bertoni[8] summarized CFLOS observations that were made from 30,000 ft to the ground over the northern hemisphere.

Big as the above-mentioned efforts may have been, they fail to provide probability estimates of cloud cover, or of CFLOS, in layers, or at specified levels. While it is conceivable that the new tools of meteorology will provide them someday, to the greater benefit of our climatological knowledge, our present knowledge is short of our goals.

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1. Lund, I.A., Grantham, D.D., and Elam, C.B. (1975) Atlas of Cloud-Free Line-of-Sight Probabilities, Part 1: Germany, AFCRL-TR-75-0261, ADA 013784.
2. Lund, I.A., Grantham, D.D., and Elam, C.B. (1976) Atlas of Cloud-Free Line-of-Sight Probabilities, Part 2: Union of Soviet Socialist Republics, AFGL-TR-77-0005, ADA 040705.
3. Lund, I.A., Grantham, D.D., and Elam, C.B. (1976) Atlas of Cloud-Free Line-of-Sight Probabilities, Part 3: United States of America, AFGL-TR-77-0188, ADA 051112.
4. Lund, I.A., Grantham, D.D., and Elam, C.B. (1978) Atlas of Cloud-Free Line-of-Sight Probabilities, Part 4: Europe, AFGL-TR-78-0276, ADA 065167.
5. Lund, I.A., Grantham, D.D., Bertoni, E.A., and Elam, C.B., Jr. (1979) Atlas of Cloud-Free Line-of-Sight Probabilities, Part 5: North Africa and the Middle East, AFGL-TR-79-0275, ADA 088156.
6. Rapp, S.R. (1973) Cloud-free line-of-sight calculations, J. Appl. Meteorol. 12:484-493.
7. Lund, I.A., and Shanklin, M.D. (1973) Universal methods for estimating probabilities of cloud-free lines-of-sight through the atmosphere, J. Appl. Meteorol. 12:28-35.
8. Bertoni, E.A. (1977) Clear and Cloud-Free Lines-of-Sight from Aircraft, AFGL-TR-77-0141, ADA 046352.

The steps in the model application are:

(a) A review of model B, which is a model of weather conditions occupying horizontal space,[9, 10] and its application to cloud-cover climatology.

(b) Estimation of the two Model B parameters: a vertical single-line cloud probability ($\overline{P}_\infty$) and scale distance (r).

(c) Use of the two Model B parameters to estimate the probability distribution of total cloud cover as a function of areal size. (The RUSSWO provides only data for the sky cover as the ground observer sees it.)

(d) Estimation of the average cloud cover, from the ground up.

(e) Estimation of the average cloud cover in a layer between specific altitudes and the average cloud presence at any level.

(f) Approximation of the frequency distribution of cloud cover in any layer or at any level.

(g) The relation of cloud cover to CFLOS.

2. MODEL B

Gringorten[10] presents and describes Model B and its applications to weather conditions occupying a line or an area. It would be redundant to repeat all of the details of the Journal of Applied Meteorology paper, with its 20 pages, 31 figures and 12 tables. But 11 figures, Figures 1(0) to 1(10), need to be presented in more detail, largely to make the graphs more useful. To illustrate the use of the charts for cloud cover, suppose the probability $\overline{P}_\infty$ of a cloud intercept directly overhead is

$$\overline{P}_\infty = 0.75$$

In this case $\overline{P}_\infty$ is the probability that the threshold is equalled or exceeded. [This example is illustrated by the broken lines of Figure 1(0)]. This probability has an equivalent normal deviate (END) symbolized as y_∞, which can be read in any table of the normal probability integral:

$$y_\infty = -0.6745$$

9. Gringorten, I.I. (1976) Areal Coverage Estimates by Stochastic Modeling, AFGL-TR-76-0148, ADA 031299.

10. Gringorten, I.I. (1979) Probability models of weather conditions occupying a line or an area, J. Appl. Meteorol. 18:957-977.

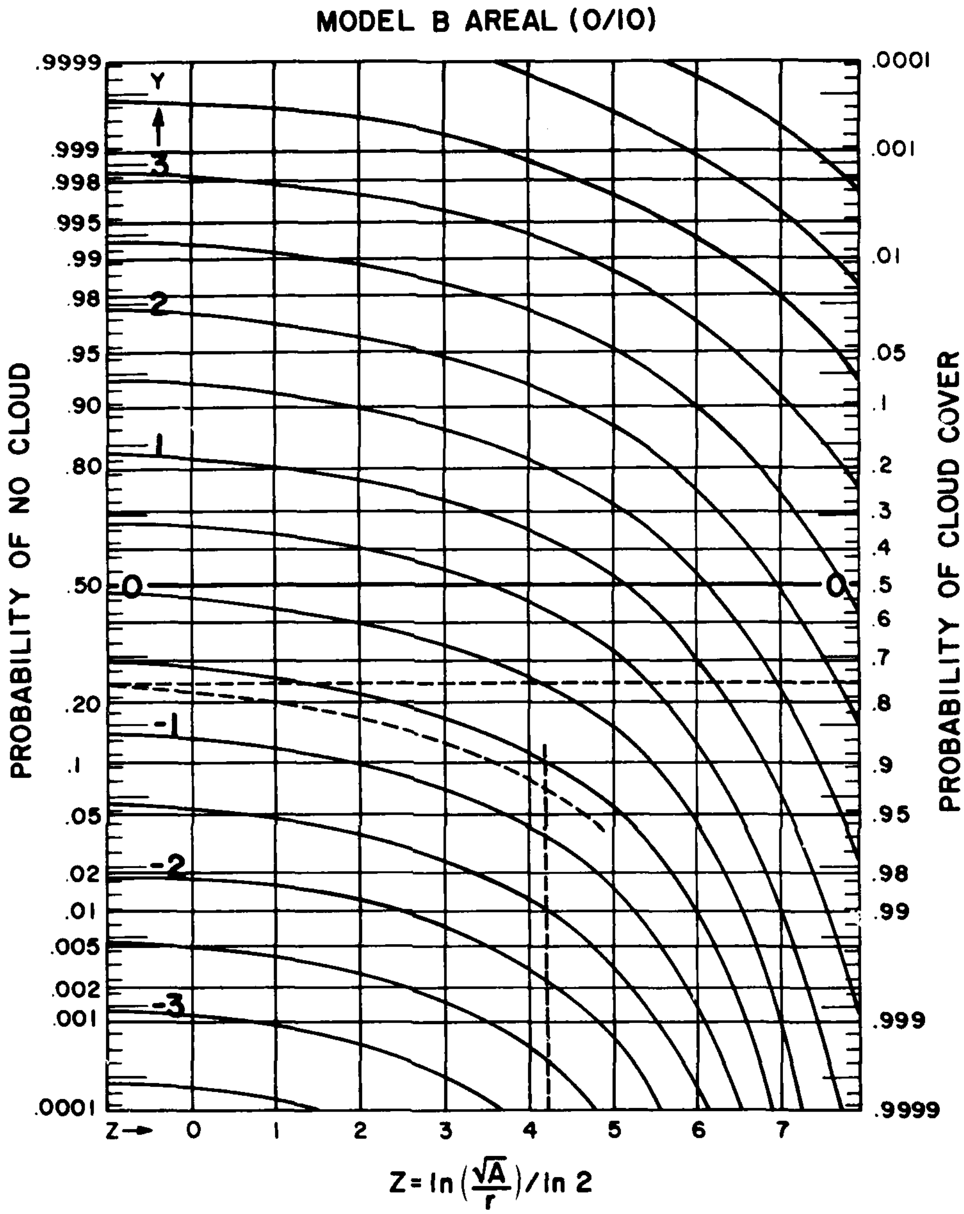

Figure 1(0). Model B Probability Estimates of Zero Cloud Cover ($x = 0/10$) in the Area s^2. The horizontal scale is uniform in $z = \ln s/\ln 2$. Instruction: The mean cloud cover, or the single-point probability of cloudiness is found on the probability scale on the right. The complementary probability of single-point no-cloud is read on the left-hand scale. The corresponding y-curve can be followed to its intersection with the z-value of the area s^2. The probability $P_{\infty}(x)$ that the fraction of cloud cover will be less than or equal to x in the area s^2 is read on the left-hand scale

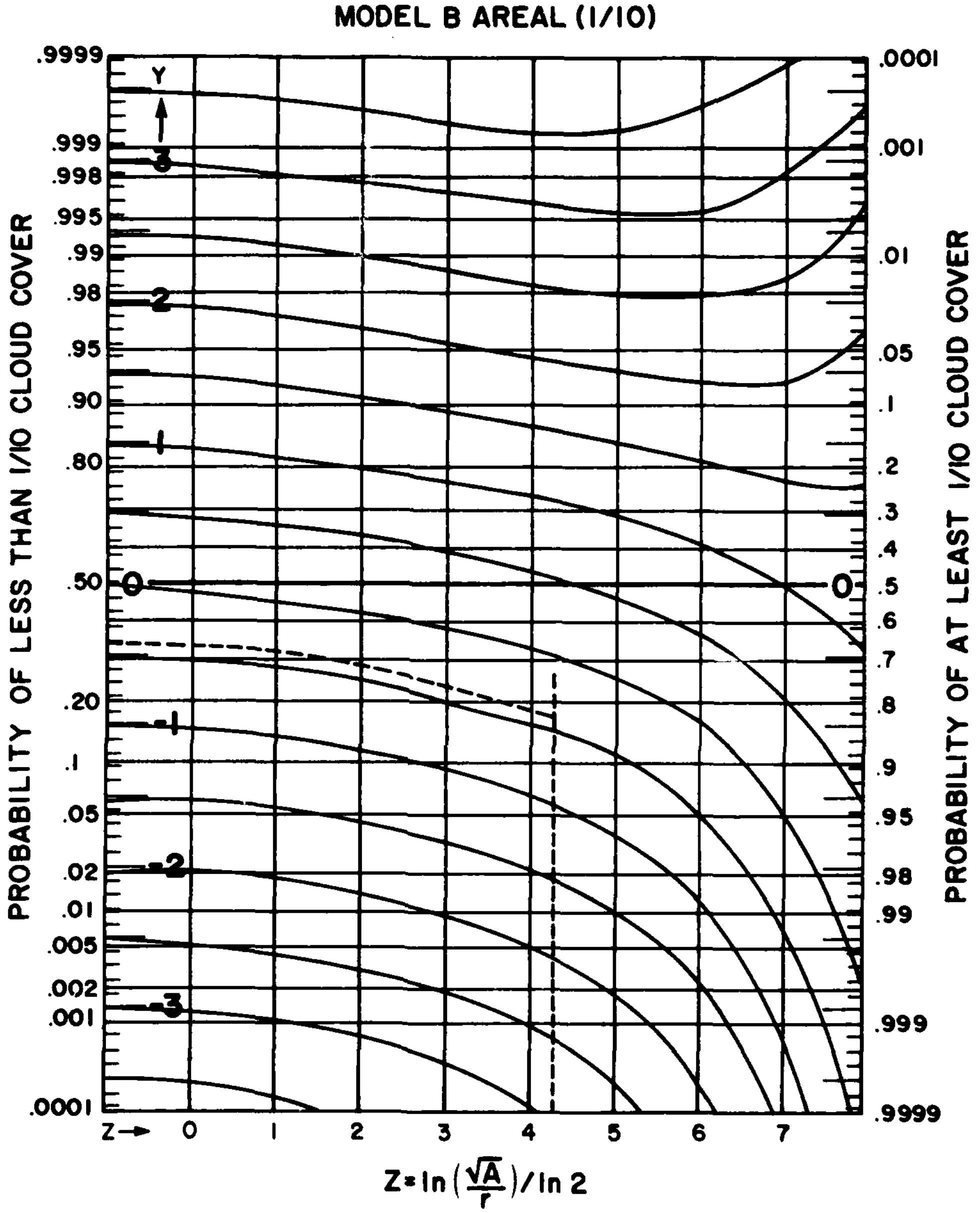

Figure 1(1). Model B Probability Estimates of Cloud Cover ($x \leq 1/10$) in the Area s^2. See instruction with Figure 1(0)

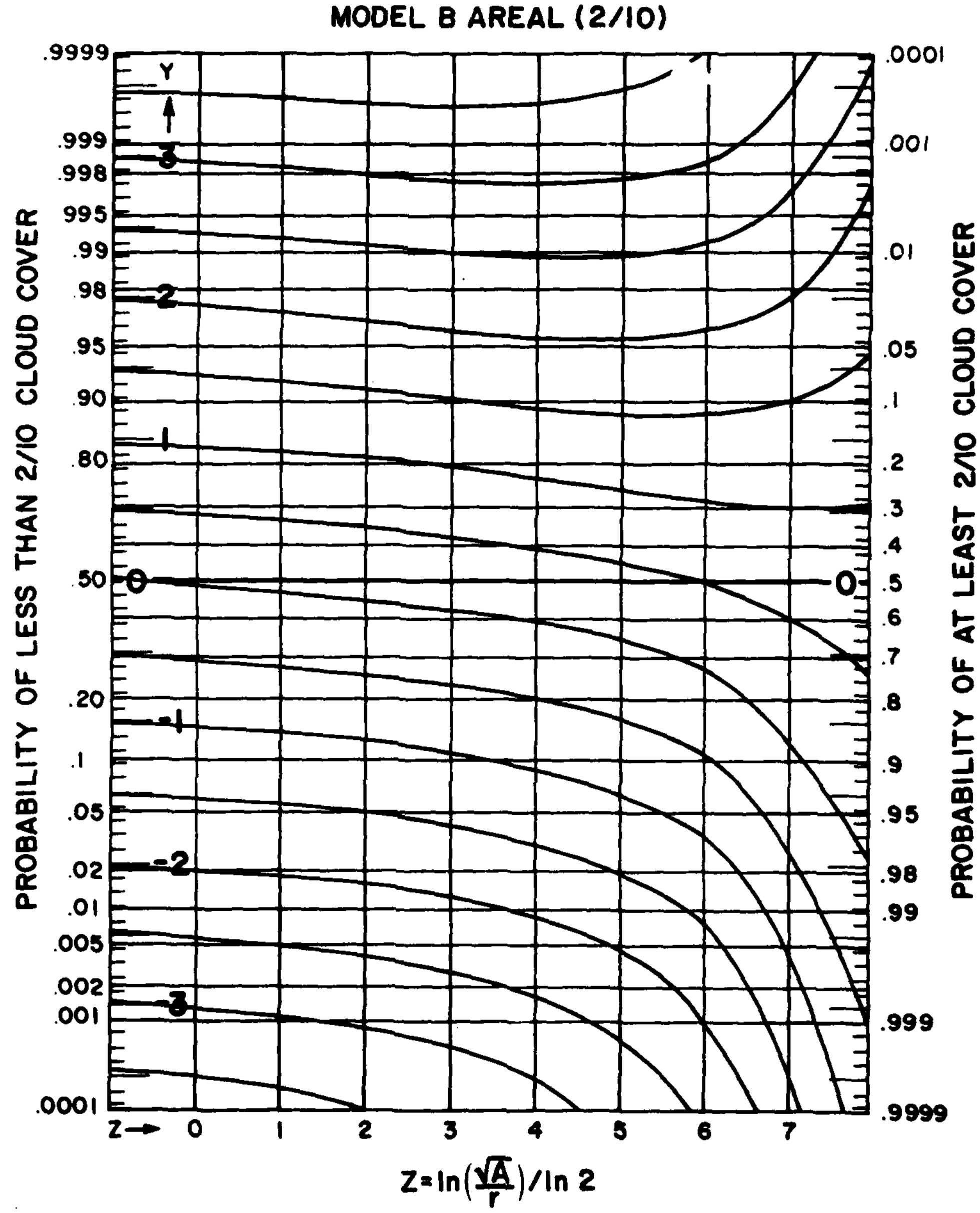

Figure 1(2). Model B Probability Estimates of Cloud Cover ($x \leq 2/10$) in the Area s^2. See instruction with Figure 1(0)

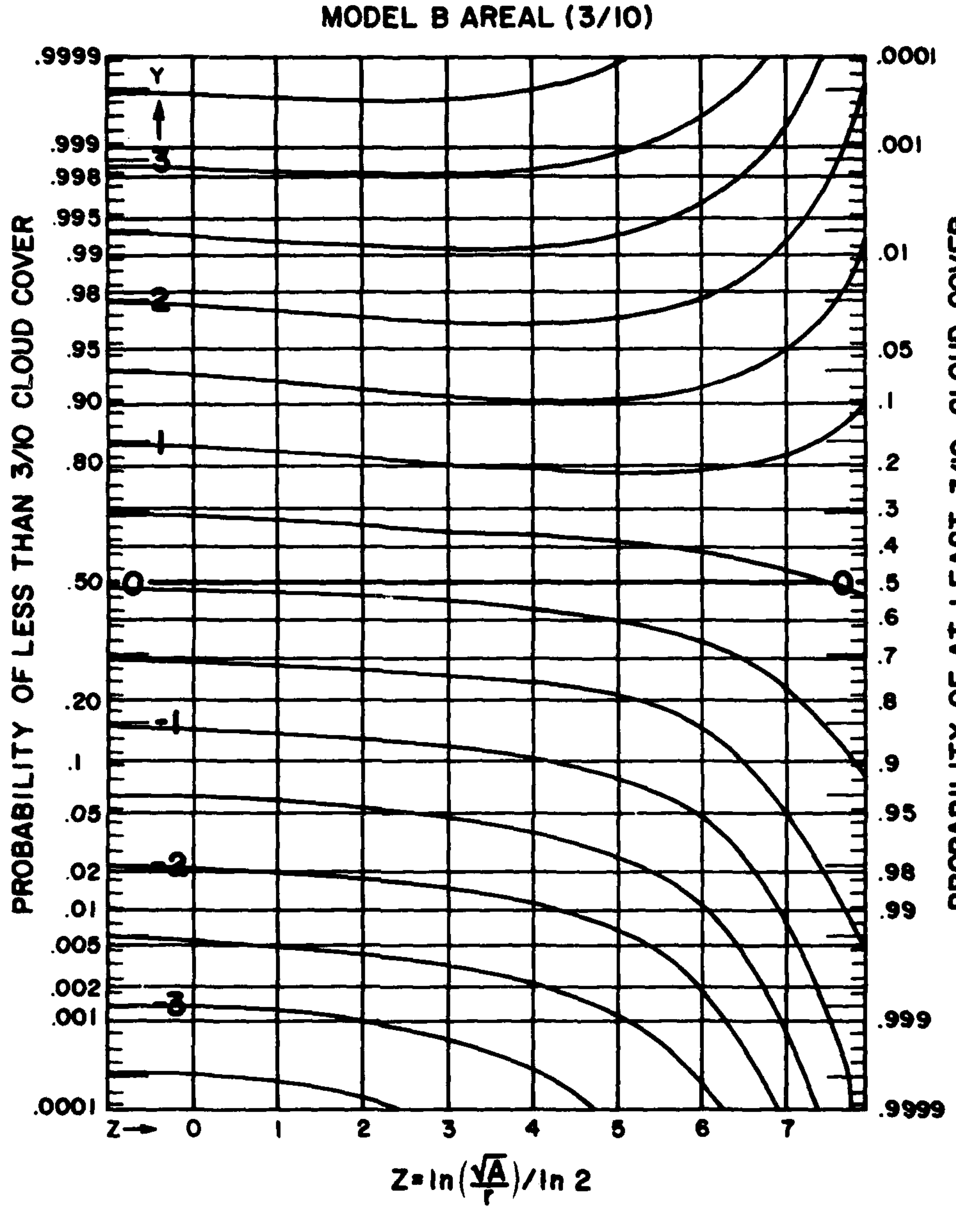

Figure 1(3). Model B Probability Estimates of Cloud Cover ($x \leq 3/10$) in the Area s^2. See instruction with Figure 1(0)

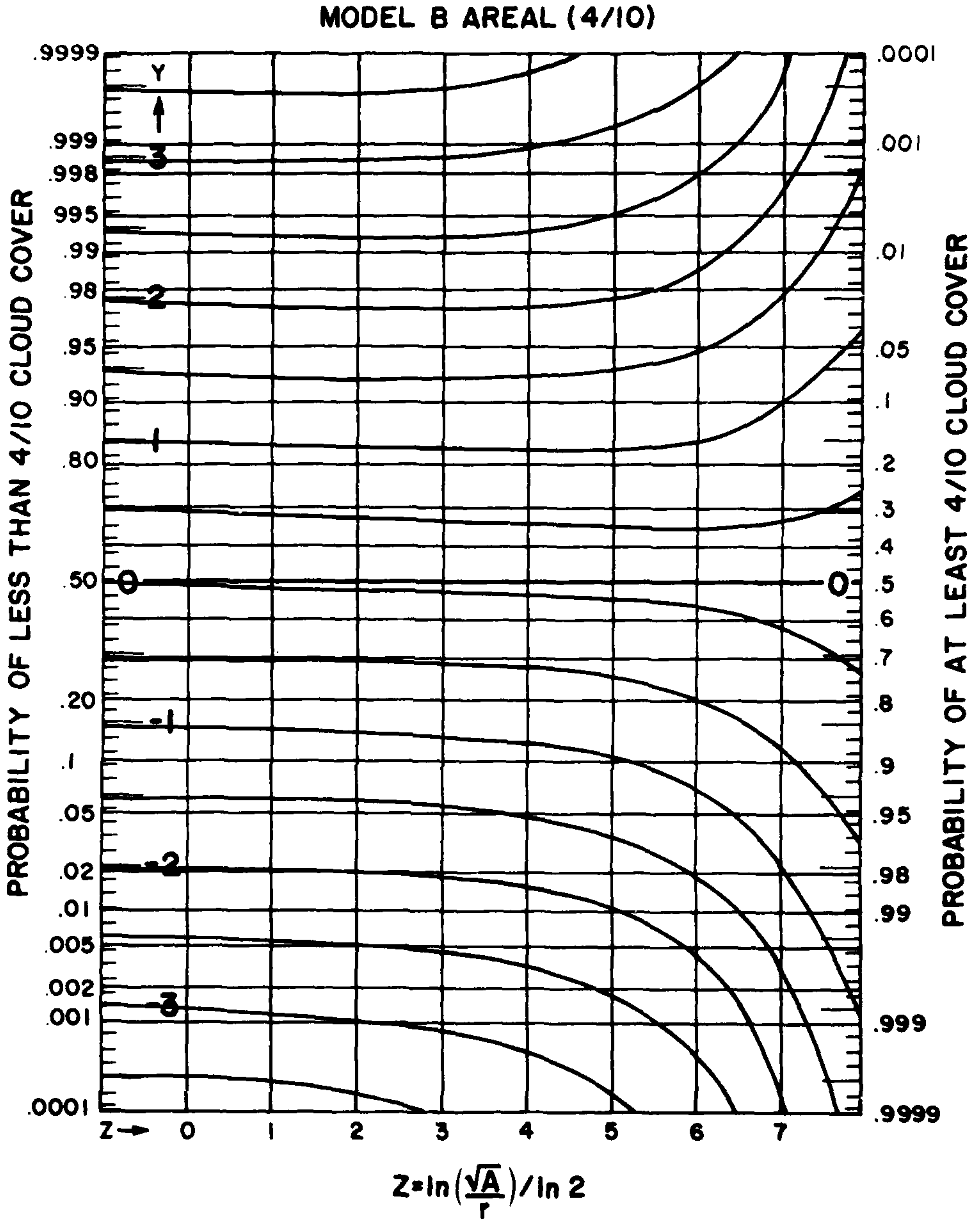

Figure 1(4). Model B Probability Estimates of Cloud Cover ($x \leq 4/10$) in the Area s^2. See instruction with Figure 1(0)

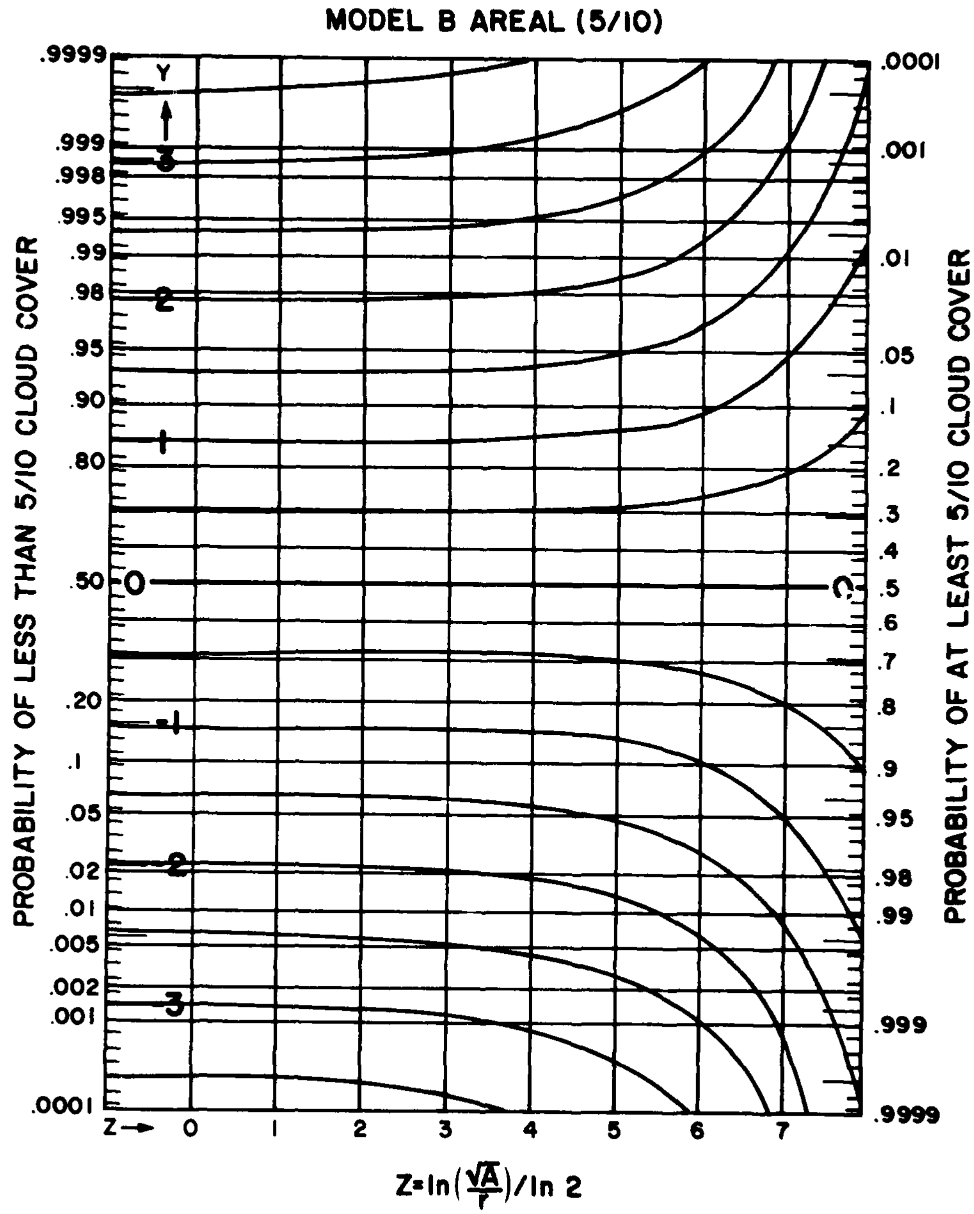

Figure 1(5). Model B Probability Estimates of Cloud Cover ($x \leq 5/10$) in the Area s^2. See instruction with Figure 1(0)

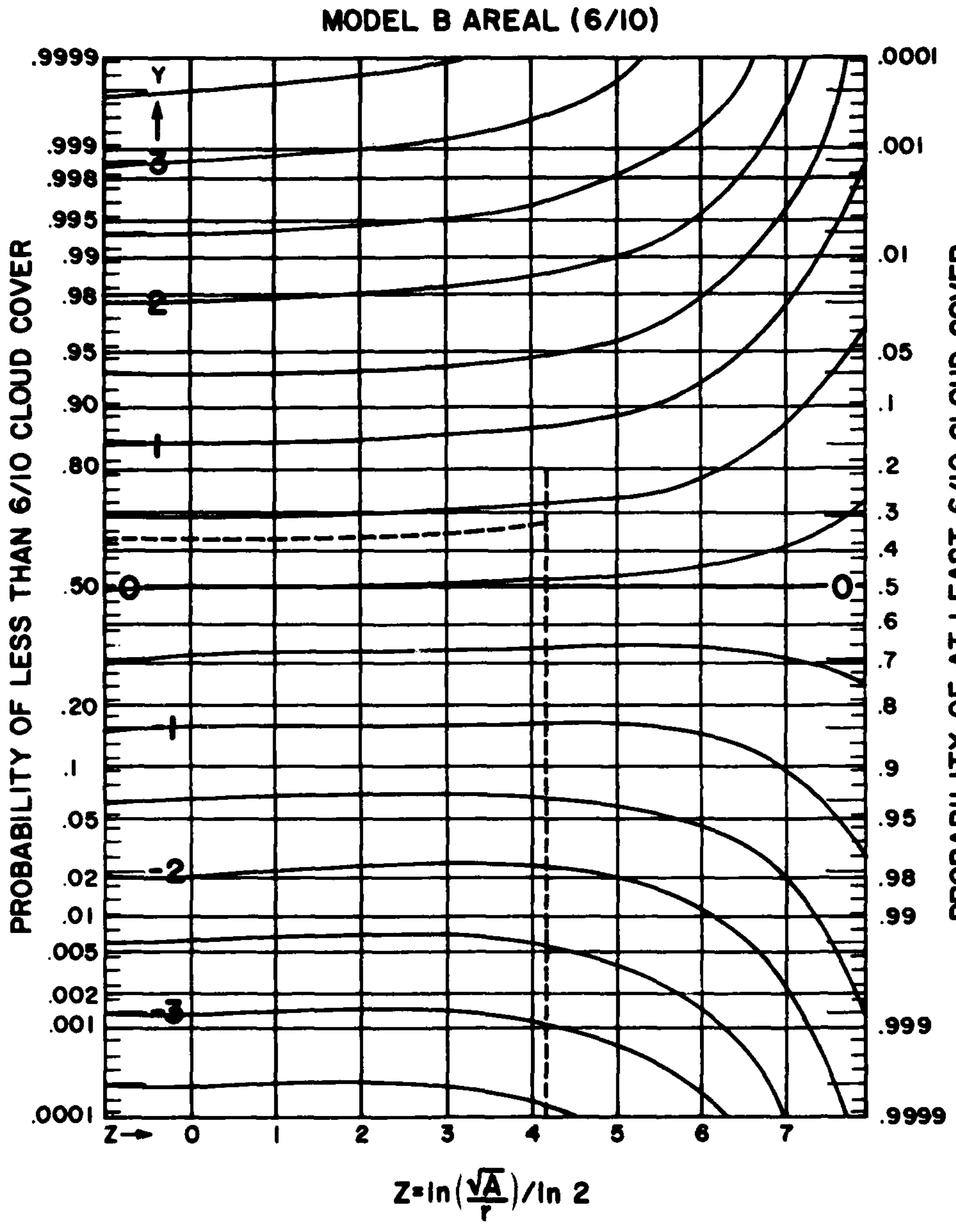

Figure 1(6). Model B Probability Estimates of Cloud Cover ($x \leq 6/10$) in the Area s^2. See instruction with Figure 1(0)

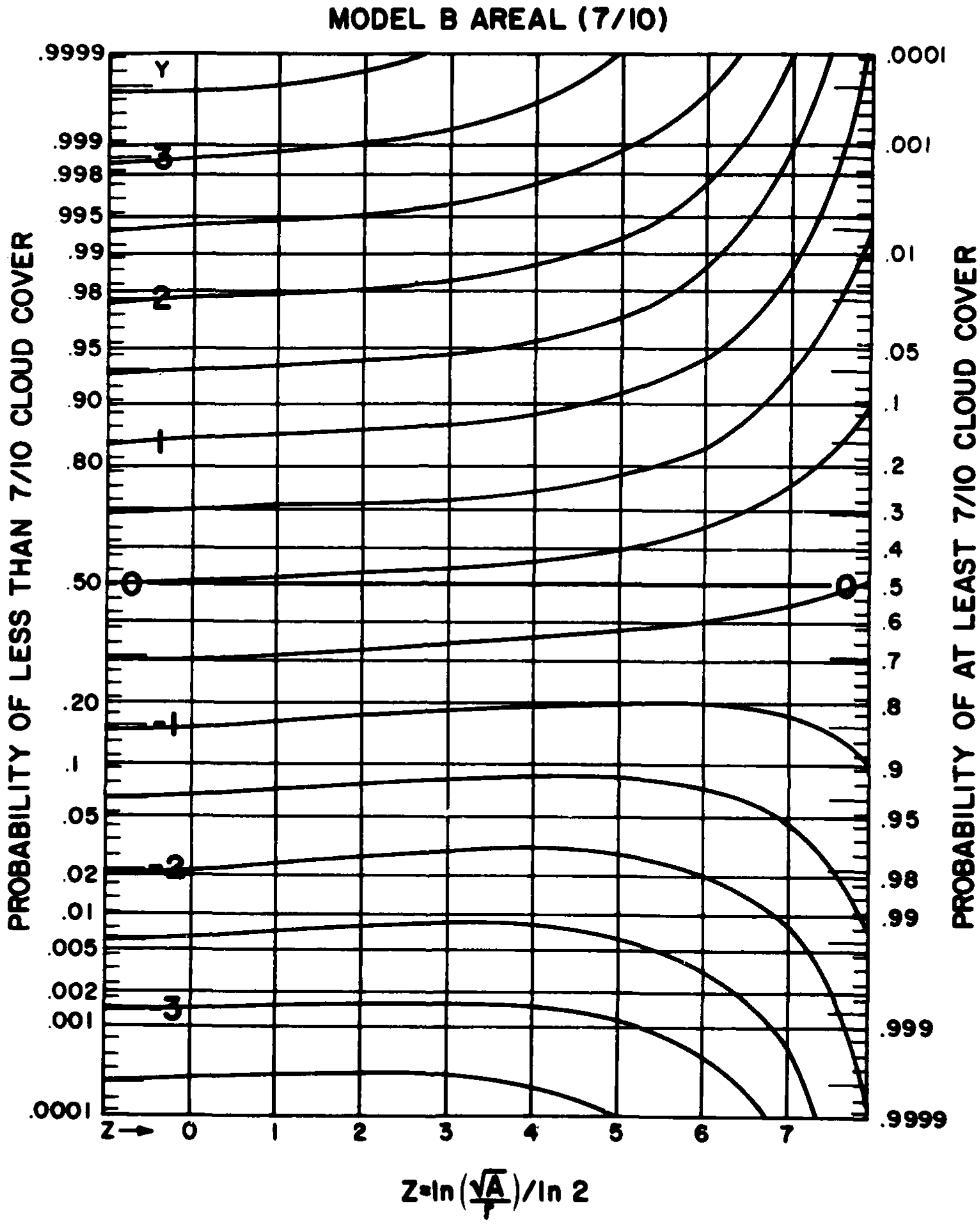

Figure 1(7). Model B Probability Estimates of Cloud Cover ($x \leq 7/10$) in the Area s^2. See instruction with Figure 1(0)

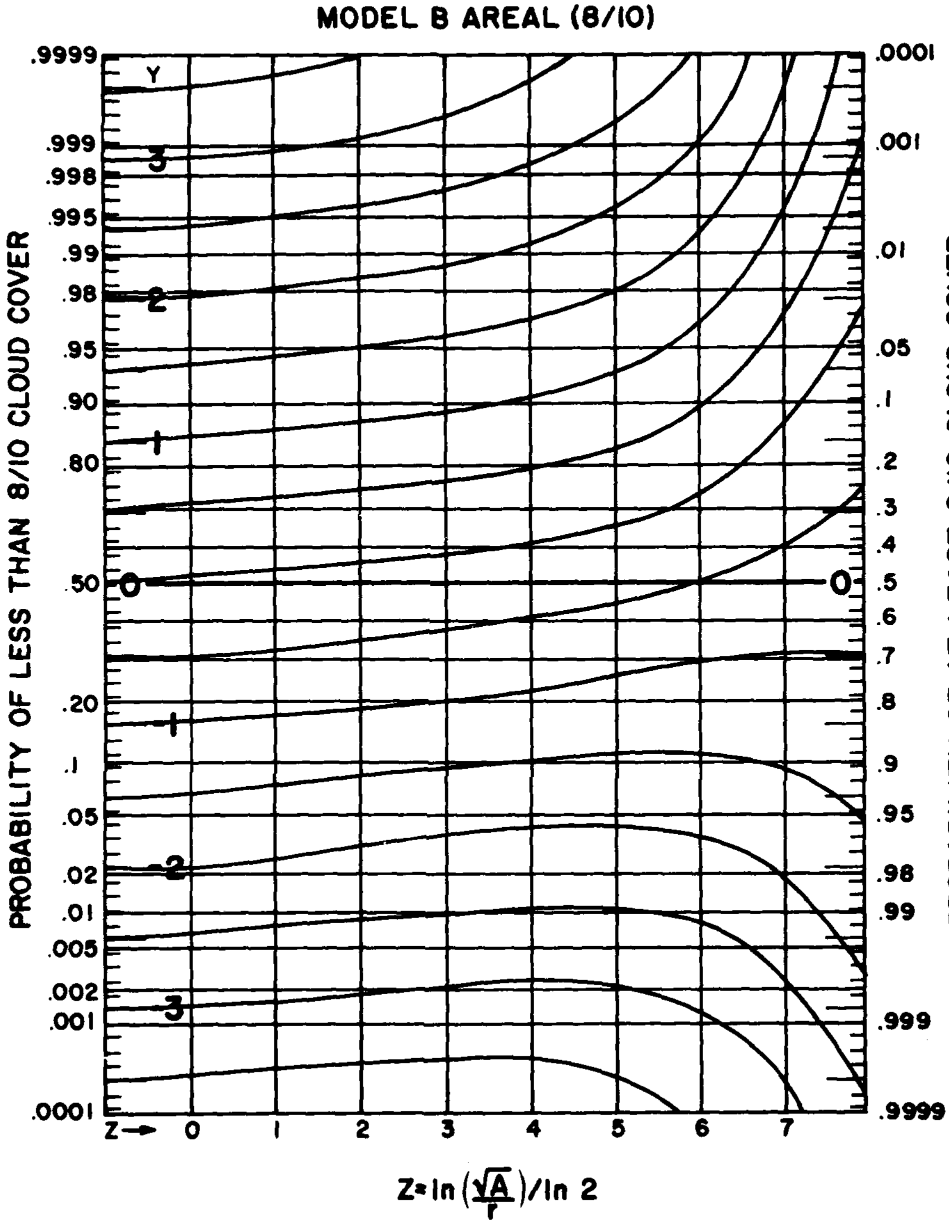

Figure 1(8). Model B Probability Estimates of Cloud Cover ($x \leq 8/10$) in the Area s^2. See instruction with Figure 1(0)

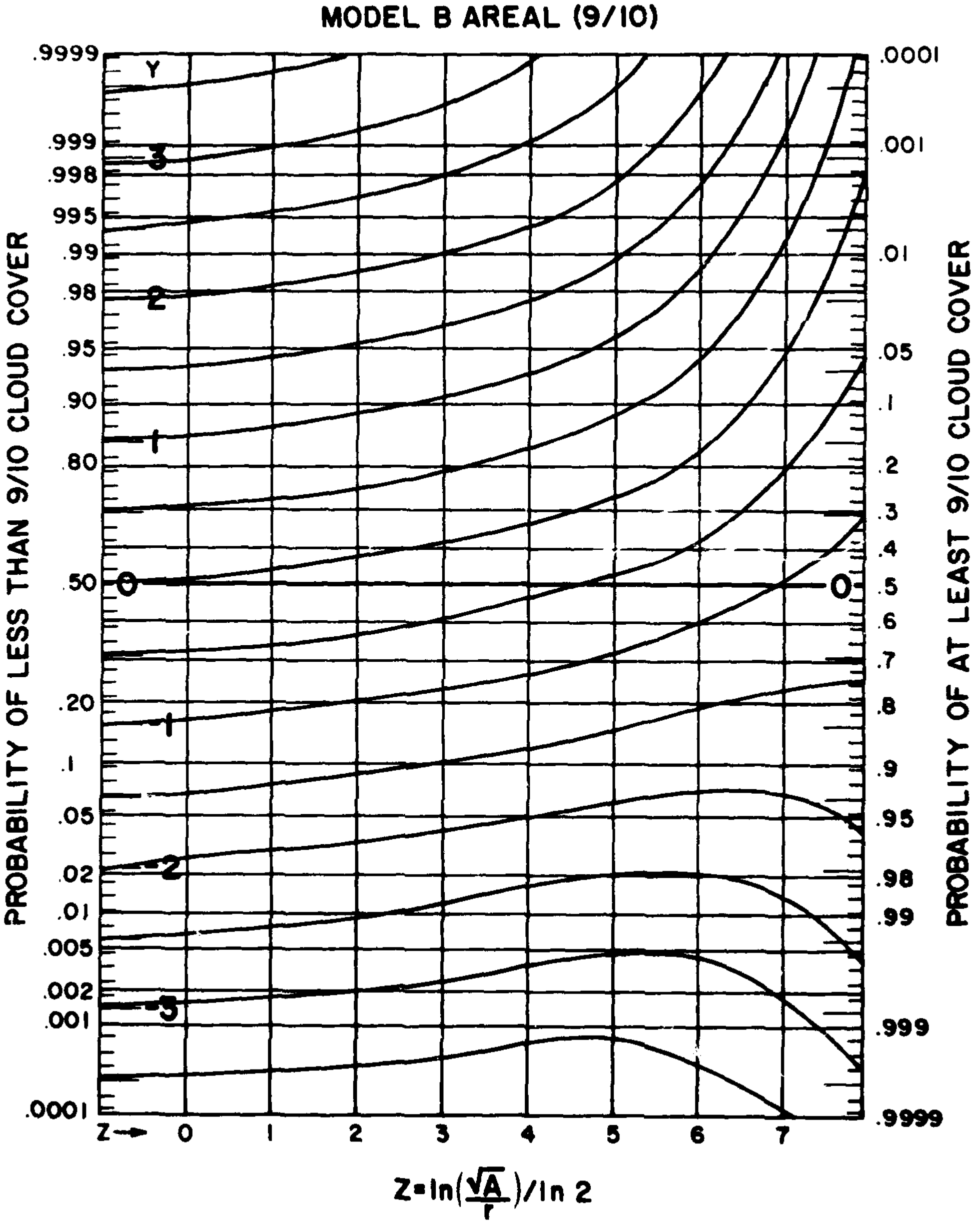

Figure 1(9). Model B Probability Estimates of Cloud Cover ($x \leq 9/10$) in the Area s^2. See instruction with Figure 1(0)

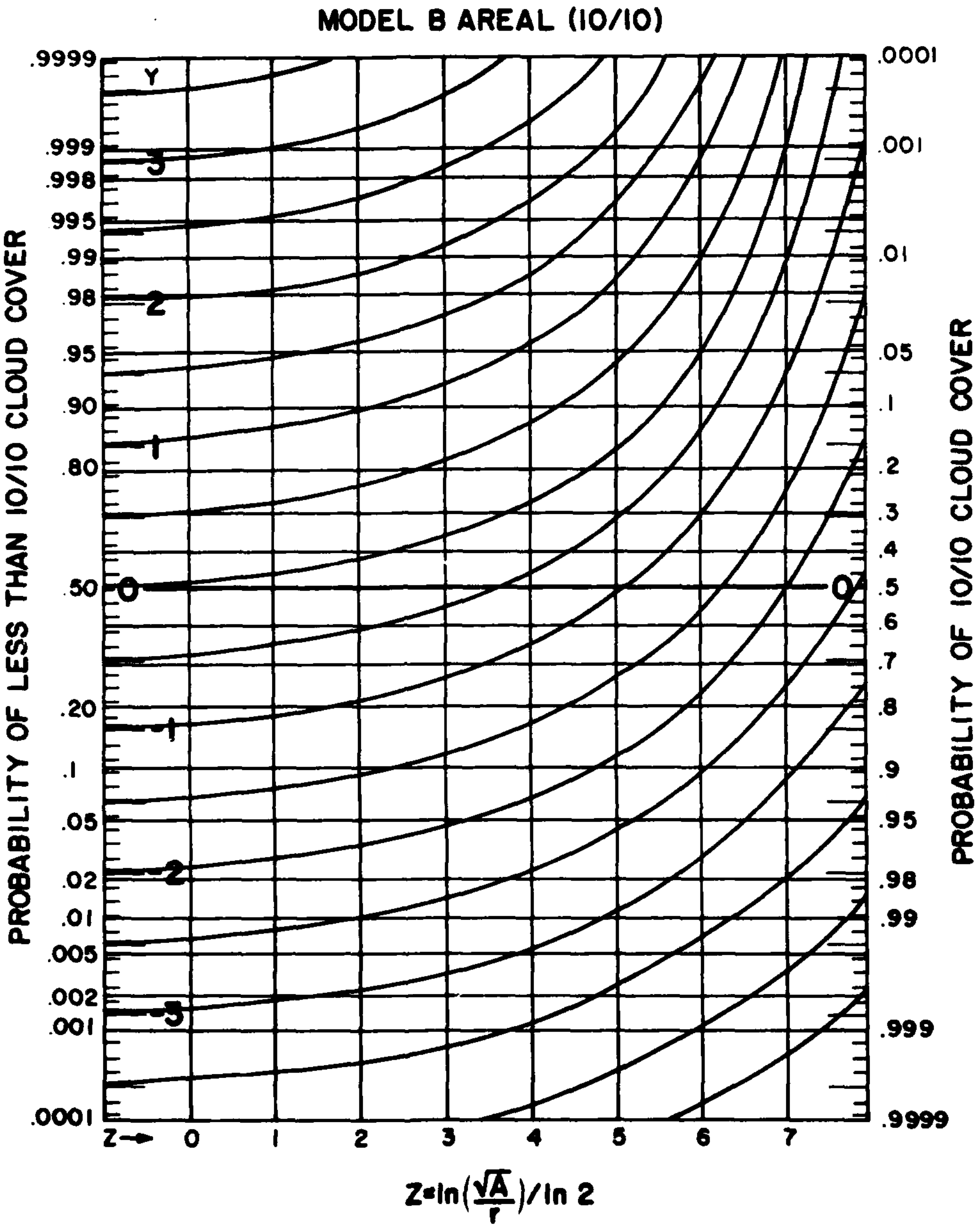

Figure 1(10). Model B Probability Estimates of Full Overcast (x = 10/10) in Area s^2. The single-point probability of cloud cover is found on the right-hand side, and the complementary probability of single-point no-cloud is read on the left-hand side. The corresponding y-curve can be followed till its intersection with the z-value of area s^2. The probability of (10/10) cloud cover in the area s^2 is read on the right-hand scale

On each chart the curve (interpolated) of $y = -0.6745$ starts on the left-hand side of the chart and is the one that concerns us here.

On the horizontal axis of Figures 1(0) to 1(10), the scale is uniform in z where

$$z = \frac{\ell n\, s}{\ell n\, 2} \tag{1}$$

where

$$s = \frac{s'}{r} = \frac{\sqrt{A}}{r} \tag{2}$$

where A is the area over which the cloudiness is being considered, and s' is the linear dimension of the square whose area is A. The parameter r is known as the scale distance. In a perfectly fitting model, the scale distance would be the distance over which the correlation coefficient is 0.99.

Within the constraints of geographic location, time of day, and time of year, there is a value for the scale distance r for cloud cover which is reasonably stable. As described in Section 3, below, for Bedford, Mass., in January, from 1200 to 1400 LST,

$$r = 2.62 \text{ km} \quad .$$

When r is entered into Eq. (2), the dimensionless number s is found. When the value of s is entered in Eq. (1), a value of z is found that can be entered on the abscissa scale of Figures 1(0) to 1(10).

Suppose r = 2.62 km. For A let the area of concern be that which can be seen by the observer, assumed to have a 15 nm or 27.8 km radius (see Section 3, below). Then

$$s' = A = 49.24 \text{ kn}$$

Hence, from Eq. (2)

$$s = 18.8$$

and from Eq. (1)

$$z = 4.23 \quad .$$

The single vertical-line probability (0.75) of the event (cloud cover) is read on the right-hand scale of Figure 1(0-10); the probability of the non-event (no cloud), 0.25, is read on the left-hand scale. The probability of no cloud is $(1 - \bar{P}_{\infty})$. Over an area the probability of no cloud must be less, and must decrease as the size of the area increases. We must find $(1 - \bar{P}_{\infty}) = 0.25$ on the left-hand scale of Figure 1(0) and follow the curve of $y = -0.6745$ to the correct areal size as signified by $z = 4.23$ on the abscissa. The probability of no (0/10) cloud cover anywhere in the area corresponding to $z = 4.23$ is reduced to 0.076, as read on the left-hand scale.

Figure 1(2) shows that the probability of cloud cover of (2/10) or less in the area corresponding to $z = 4.23$ is 0.16.

Figure 1(9) shows that the probability of 9/10 or less cloud cover in the area corresponding to $z = 4.23$ is 0.40. From Figure 1(10) the probability of overcast in the area corresponding to $z = 4.23$ can be read on the right-hand scale as

$$P_{\infty}(10/10) = 0.50 \ ,$$

or the probability of (10/10) overcast is 50 percent, when the single-line (overhead) probability $(\bar{P}_{\infty})$ is 75 percent.

Since ceilings are formed by a cloud cover of 6/10 or more, Figure 1(6) gives the corresponding probability of a <u>ceiling</u>, over the area (A). At $z = 4.23$, it is read on the right-hand scale as 0.72, or

$$P_{\infty}(6/10) = 0.28$$

The probability of 10/10 cloud cover decreases with increasing size of the area. But, as shown by Figure 1(6), the probability of the partial cover ($<6/10$) increases very little with areal size, up to approximately 7000 km^2, ($z \approx 5$). For still larger areas, however, the probability of less than 6/10 cloud cover decreases toward zero, as long as the mean cloudiness exceeds 60 percent. (It was given as 75 percent).

3. ESTIMATES OF MODEL B PARAMETERS r AND $\bar{P}_{\infty}$

For a first approximation, assume that the <u>mean sky cover</u> is equal to the probability of a single-line cloud intersect vertically above the observer. It is symbolized by $\bar{P}_{\infty}$. This assumption may be unacceptable to some investigators,

specifically to such authors as McCabe[11] and Lund and Shanklin[7] who have shown that the probability of a CFLOS depends upon the viewing angle (see Section 8 below). However, with all the difficulties that we must face with respect to cloud cover, this assumption may not be bad.

For each of eight 3-hour periods of the day the RUSSWO yields the frequency of sky cover, $P_\infty(x)$ for x = 0.0 to 1.0, and also the mean sky cover ($\bar{P}_\infty$). Unless otherwise specified, the illustration for the remainder of this paper is limited to the cloud cover of Bedford, Mass., in January, from 1200 to 1400 LST. In the 1943-1965 Bedford RUSSWO, cloud cover is given in tenths (Table 1). In the illustration, the mean sky cover is 0.66, or the single-line probability of a cloud is $\bar{P}_\infty = 0.66$.

Table 1. The RUSSWO Figures for the Frequency, $p_\infty(x)$, (Note Lower Case p) of Sky Cover (x) at Bedford, Mass., in January, From 1200 to 1400 LST, Followed by the Cumulative Frequency, $P_\infty(x)$, and the Corresponding Estimates of z. Vertical single-line probability ($\bar{P}_\infty$) is 0.66; the equivalent normal deviate (END) is $y_\infty = -0.41$

Sky Cover x	Frequency $p_\infty(x)$	Cumulative Frequency $P_\infty(x)$	Model B $\hat{z}$
Clear 0.0	0.155		
0.1	0.043	0.176	4.32
0.2	0.049	0.222	4.33
0.3	0.041	0.268	4.30
0.4	0.041	0.308	4.20
0.5	0.031	0.344	--
0.6	0.027	0.374	--
0.7	0.044	0.409	3.95
0.8	0.060	0.461	4.32
0.9	0.046	0.514	4.16
1.0 Overcast	0.462		Average z = 4.23 r = 2.62

11. McCabe, J.T. (1965) Estimating Mean Cloud and Climatological Probability of Cloud-Free Line-of-Sight, Technical Report 186, Air Weather Service, USAF.

The value $\bar{P}_\infty$ becomes a key parameter in this modeling. It can have dramatically different values depending on month and time of day. Figure 2 displays information assembled from the Bedford RUSSWO on the mean cloud cover. Generally speaking, the cloudiness is greatest in April or May, least in September or October, greatest at noon, and least at midnight. The mean cloudiness varies from 0.43 to 0.70, a range that straddles the critical value of 0.6 which constitutes a ceiling.

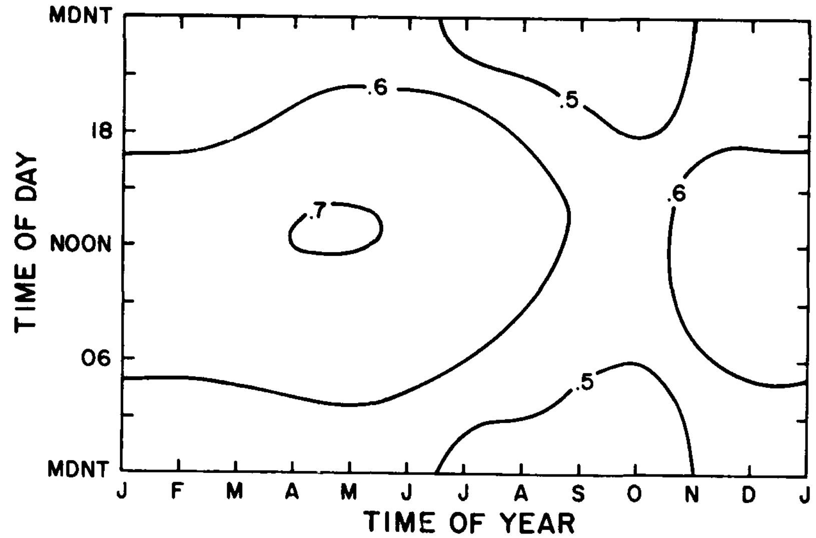

Figure 2. The Average Sky Cover as a Function of Month of Year and Time of Day, at Bedford, Mass. (1943-1967 Record)

The sky dome has been assumed to have a radius of 15 nm or 27.8 km, an estimate that is supported by studies of satellite cloud amounts compared with surface observations of sky cover by Barnes and Chang.[12] The corresponding area is

$$A = 2424 \text{ km}^2$$

whose equivalent square region has the linear dimension

$$s' = 49.24 \text{ km} .$$

12. Barnes, J. C., and Chang, D. (1968) Accurate Cloud Cover Determination and its Effect on Albedo Computations, Final Report, Contract No. NAS-5-10478, Allied Research Associates, Concord, Mass.

Because sky cover is estimated by the observer to the nearest tenth of the sky dome, the category zero includes 0 to 0.05 sky cover; 1/10 includes 0.06 to 0.15; ... 10/10 includes 0.96 to 1.0. Therefore, given the 11 frequencies $p_\infty(x)$ (from the RUSSWO) of the sky cover, x = 0.0(0.1)1.0, the 9 cumulative frequencies for x = 0.1(0.1)0.9, were estimated by use of:

$$P_\infty(x) = \sum_{\xi=0}^{(x-0.1)} p_\infty(\xi) + p_\infty(x)/2 \qquad (3)$$

Equation (3) was used to obtain the nine cumulative frequencies $P_\infty(x)$ in Table 1. After the column for $P_\infty(x)$ was completed each successive value was used in the corresponding graph, Figures 1(1) to (9), to find $\hat{z}$. The mean sky cover is 0.66, whose equivalent normal deviate (END) is y = -0.41. Beginning with Figure 1(1) for 1/10 areal coverage, the y-curve (y = -0.41) is followed until the intersection is found with $P_\infty(x)$. [The broken lines on Figure 1(1) illustrate this example.]

From Table 1, $P_\infty(1) = 0.176$. Following the y = -0.41 curve to the point

$$P_\infty(1) = 0.176$$

(as read on the left-hand scale), the abscissa scale shows the estimate of z to be

$$\hat{z}_1 = 4.32$$

(Another user might have read it a little differently.)

Likewise, Figure 1(2) gave, for y = -0.41 and $P_\infty(2) = 0.222$,

$$\hat{z}_2 = 4.33 \;,$$

and so on. The average of seven estimates is z = 4.23.

One test of the model's applicability is the consistency of the estimates for the z values. If the model were perfect, all estimates of z should be the same.

To find the scale distance r corresponding to the average z:

$$r = s'/s = s'/2^z \qquad (4)$$

For Bedford, Mass., in January, from 1200 to 1400 LST, corresponding to z = 4.23, r = 2.62 km, Table 1 shows estimates for z ranging from 3.95 to 4.33, a mean of 4.23, and standard deviation of 0.13. Figure 3 shows the results for scale distance r at Bedford, Mass., as a function of month of year and hour of

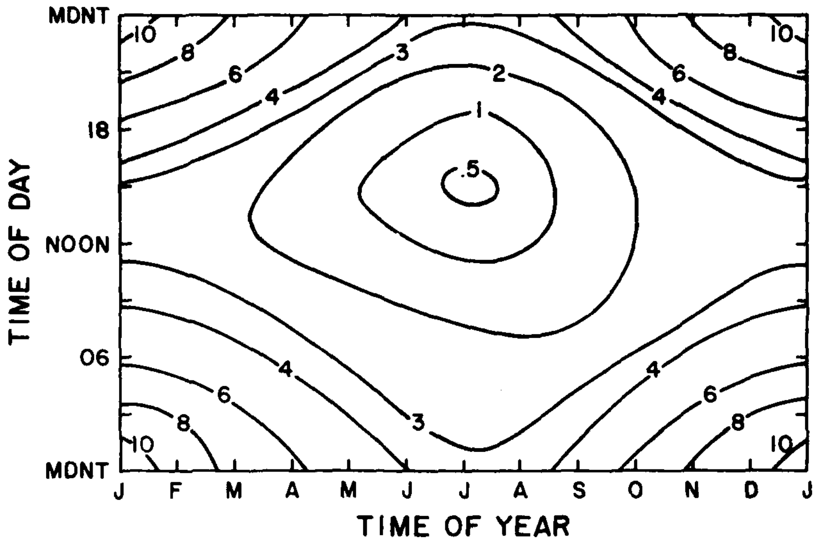

Figure 3. Isopleths of the Scale Distance (km) of Model B for Sky Cover, as a Function of Month of Year and Time of Day, at Bedford, Mass. (1943-1967 Record)

the day. Typically it shows a maximum in winter at midnight, and a minimum in summer in the afternoon. The larger the value of r, the more widespread the cloud cover should be, which we can expect from winter frontal storms. On the other hand, the summer storms are more likely to be of an air-mass local nature, of the cumuliform type; they develop most frequently in the afternoon, each cloud on a relatively small scale. Hence, summertime values of r are expected to be small.

In summary, we have applied Model B to the sky-cover data of the RUSSWO, to yield scale distance (r). The average sky cover or the single vertical-line probability of cloud intercept, ($\overline{P}_\infty$) is given by the RUSSWO directly. The next section deals with the application of the model, with these two parameters known.

4. APPLICATION OF MODEL B TO ESTIMATE CLOUD COVER PROBABILITIES

When the parameter values for scale distance and mean sky cover (r, $\overline{P}_\infty$) are known, or predetermined, the application of Model B is a straightforward use of Figures 1(0) to 1(10). (One might wish for analytical expressions or computer software to make the calculations. But at this state of the investigation, we settle for graphical solutions.)

For Bedford, Mass., in January, from 1200 to 1400 LST, $r = 2.62$ km and $\overline{P}_\infty = 0.66$. For areas (A) of 100 km^2, 2424 km^2, and 100,000 km^2, Eqs. (1) and (2) give z equal to 1.93, 4.23, and 6.92, respectively. For the single-point

probability of 0.66, for which y = -0.41, enter each of Figures 1(0) to 1(10) successively with y = -0.41 and follow the curve to each of the three values of z successively. Values for $P_\infty(x)$, x = 0 (0.1)1.0 are obtained as shown in Table 2. For comparison, Table 2 gives the RUSSWO-derived frequencies for the sky dome. The root mean square difference of the first 10 estimates is 0.005.

Table 2. Model B Estimations, $P_\infty(x)$, of Cumulative Probabilities of Cloud Cover (x) for Several Areas of Varying Sizes. Example is for Bedford, Mass., in January, From 1200 to 1400 LST, r = 2.62 km, $\bar{P}_\infty$ = 0.66 or y_∞ = -0.41

Cloud Cover x	Area Size (A) $(km)^2$			
	100 z = 1.93	2424 (Sky Cover) z = 4.23 Model Estimate	2424 (Sky Cover) z = 4.23 RUSSWO	100,000 z = 6.92
Clear 0	0.25	0.125	0.132	negligible
0.1	0.27	0.18	0.176	0.016
0.2	0.285	0.23	0.222	0.046
0.3	0.30	0.27	0.268	0.100
0.4	0.33	0.305	0.308	0.177
0.5	0.34	0.34	0.344	0.26
0.6	0.36	0.38	0.374	0.38
0.7	0.37	0.410	0.409	0.52
0.8	0.380	0.46	0.461	0.65
0.9	0.43	0.52	0.514	0.81
1.0 Overcast	0.57*	0.40*	0.440*	0.011*

*Probability of overcast only

5. MEAN SKY COVER $\overline{P}_H$ AS A FUNCTION OF ELEVATION H ABOVE GROUND

A ceiling is a cloud deck that covers 6/10 or more of the sky dome. Table 3 shows the frequency F_H of ceiling heights H for Bedford, Mass., in January, from 1200 to 1400 LST, as read from the RUSSWO, but converted to give the heights less than H. As before, it is assumed that the observer views the sky within a radius of 15 nm or 27.8 km, to make the linear dimension $s' = 49.24$ km.

Table 3. Cumulative Frequency F_H of Ceiling Heights Less than H at Bedford, Mass., in January, From 1200 to 1400 LST, as Obtained From the RUSSWO. Estimates of the Equivalent Normal Deviate (END) Y_H and single vertical-line probability $\overline{P}_H$ are obtained from Model B [Figure 1(6)]. Assumed scale distances: $r = 2.62$ km, $z = 4.23$

Height H (ft)	F_H	Y_H	$\overline{P}_H$
< 100	0.006	2.30	0.011
< 200	0.019	1.90	0.029
< 300	0.032	1.70	0.045
< 400	0.048	1.50	0.067
< 500	0.062	1.40	0.081
< 1000	0.139	0.93	0.171
< 2000	0.195	0.72	0.236
< 3000	0.247	0.55	0.291
< 4000	0.295	0.40	0.339
< 5000	0.325	0.33	0.367
< 10,000	0.401	0.15	0.440
< 20,000	0.496	-0.08	0.524
All ceiling	0.555	-0.23	0.591

For the whole sky cover the scale distance at Bedford, Mass., in January, at noon, was estimated at $r = 2.62$ km, for which Figure 1(6) is entered at $z = 4.23$

(see above). The scale distance r is spatially conservative, although found to vary significantly with season and time of day (Figure 3). So far, r was found for the sky cover regardless of height of clouds.

The assumption is made, now, that the same r will serve as the scale distance for all clouds at any level, or clouds between any two levels. This assumption is discussed in Sections 9 and 10.

For Bedford, Mass., in January, from 1200 to 1400 LST the frequency of ceilings, for all heights, is shown as $F_{\infty} = 0.555$. Unfortunately, this does not agree with the frequency of cloud cover equal to or greater than 6/10 in the RUSSWO sky-cover table, which shows it as 0.639. Upon examining the instructions in the Federal Meteorological Handbook for surface observations[13] we see a good reason for this discrepancy. A report of ceiling requires opaque clouds. Thin see-through clouds do not constitute a ceiling, although they do contribute to the cloud-cover statistics, hence their greater frequency. Under the circumstances, rather than attempt adjustments, we choose the cumulative frequency of total cloud cover as that given by the table for all ceiling heights for comparison with the cumulative frequencies to lesser ceiling heights.

In accord with the assumption in this section, one value of the scale distance (r) is adopted for all layers and levels of the atmosphere. Inserting r = 2.62 km or z = 4.23 in Figure 1(6) provides the estimates of single-point probability $\bar{P}_H$ of ceilings below the given levels H, as shown in Table 3. For example, below 5000 ft, the RUSSWO gave a ceiling probability $F_5 = 0.325$. [This example is illustrated by the broken lines on Figure 1(6)]. When read on the right-hand scale and entered into Figure 1(6) at z = 4.23, this intersects the curve $y_H = 0.33$ which corresponds to $\bar{P}_H = 0.371$ as read on the right-hand axis. Or, the single-line probability of a cloud presence below 5000 ft is 37.1 percent, as opposed to the ceiling probability of 32.5 percent. Or, the mean sky cover below 5000 ft (Bedford, Mass., in January, from 1200 to 1400 LST) is 0.371.

6. AVERAGE CLOUD COVER IN ANY LAYER OR AT ANY LEVEL

The Model B procedure, so far, has used the RUSSWO on cloud cover and ceiling height to provide the average cloud cover as a function of elevation above the ground. How can this information be extended to provide the average of the cloud cover within a specific layer of the atmosphere or at a specific level?

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13. U.S. National Weather Service (1979) Surface Observations (Federal Meteorological Handbook no. 1), 2nd ed., U.S. Government Printing Office, Washington, D.C.

The assumption had been made by previous authors (deBary and Moller, 1963;[14] McCabe, 1965 [11]) that, when an *observer sees* a fractional cover at the Hth level through the breaks in the lower levels, that fraction is the same for the rest of the Hth level, which the observer does not see. As stated by deBary and Moller, "The assumption was made that clouds are horizontally distributed at random, or that high clouds are located neither principally at the same places where the low clouds are, nor principally above the cloud gaps at lower levels."

The deBary and Moller assumption is not accepted here. In agreement with Spreen and Solomon[15] it is assumed, instead, that the visible part of the cloud deck at the higher level averages less than the average cloud presence at that upper level. If $\overline{P}_H$, $\overline{P}_{H+h}$ are the mean sky covers from the surface up to the (H)th and (H+h)th levels respectively, then

$$\overline{P}_{H+h} = \overline{P}_H + (1 - \overline{P}_H) \cdot p(H+h|H) \qquad (5)$$

where $p(H+h|H)$ is the conditional probability of a cloud intersect in the layer (h), given that no clouds are intercepted from the ground up through the lower layers.

The thinner the layer h, the less likely it is that there will be a cloud immediately above the lower clear spaces. As thickness h increases the conditional frequency of a cloud should increase, approaching the unconditional frequency for that layer. Or, the cloud presence in the layer h should become more independent of the lower levels with increasing h. This surmise can be formulated as follows:

$$p(H+h|H) = \overline{p}_h \cdot (1 - e^{-h/\alpha}) \qquad (6)$$

where α is a parameter, in the same dimensional units as the thickness (h), and $\overline{p}_h$ is the mean cloud cover in the layer h. The parameter α might be made a function of thickness h. If so, the working formula becomes:

$$\overline{P}_{H+h} = \overline{P}_H + (1 - \overline{P}_H) \cdot \overline{p}_h \left(1 - e^{-h/\alpha(h)}\right) \qquad (7)$$

or

$$\overline{p}_h = (\overline{P}_{H+h} - \overline{P}_H) \cdot (1 - \overline{P}_H)^{-1} \cdot \left(1 - e^{-h/\alpha(h)}\right)^{-1} \qquad (8)$$

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14. deBary, E., and Moller, F. (1963) The vertical distribution of clouds, J. Appl. Meteorol. 2:806-808.
15. Spreen, W.C., and Solomon, I. (1958) An indirect method for estimating the frequencies of ceiling below various altitudes and within altitude ranges, Bull. Amer. Meteorol. Soc. 39:261-265.

If this formula is to be used to find $\bar{p}_h$, a value, or formula, must be assigned for α(h). If values for ($\bar{P}_{H+h}$, $\bar{P}_H$, $\bar{p}_h$) are all observable then Eq. (8) can be used to estimate values of α(h). The published values of deBary and Moller are unique in this respect, so far as this writer knows. They were obtained by "direct observations within the atmosphere itself" in a "series of observational data" from German Weather flights during the years 1936-1940, which were "unique in [their] regularity, quality and temporal continuity." Hence, estimates of α(h) vs h (as shown in Figure 4) were obtained by solving Eq. (8), using deBary and Moller's average cloud covers from the ground up for $\bar{p}_{H+h}$ and $\bar{p}_H$ and their other layer averages for $\bar{p}_h$. There was no discernible systematic variation of α(h) with time of day or time of year. But there is a significant dependence of α on the thickness h and on the height H of the base of the layer, suggesting a relationship as follows:

$$\alpha(h, H) = a + bH^{\beta} + ch \tag{9}$$

where β must have a suitable value. By method of least squares, with some trial and error for β, the equation, when applied to the data of deBary and Moller, for H = 1 to 5 km, (H+h) = 2 to 10 km, becomes:

$$\alpha(h, H) = -1.69 + 1.94\sqrt{H} + 0.475h \tag{10}$$

where both α(h, H) and h are measured in km.

For better or for worse, in the absence of other data or other assumptions, Eq. (10) is adopted for estimating the parameter (α) in the rest of this paper, whatever the station. The value of α(h, H) thus obtained can be used in Eq. (8), together with values for the average cloud cover ($\bar{P}_H$, $\bar{P}_{H+h}$), to give estimates of the average cloud cover in layers ($\bar{p}_h$). This is expected to work best at mid-latitude continental stations, like the German stations.

The reverse application of Eqs. (8) and (10) to deBary and Moller's tabulation results in a revised average vertical distribution of cloud cover as seen from the altitudes 0-10 km (Figure 5). The curve arising from the zero point shows the degree of cloudiness as seen from the ground and is taken from deBary and Moller's table. On this curve the value at 2 km is 60 percent, meaning an observer on the ground, looking upward at a target at 2 km, would have the target obscured by clouds 60 percent of the time. The $\bar{p}_h$ values are those obtained from Eqs. (8) and (10). For example, the mean cloud cover $\bar{p}_h$ between 2 and 4 km is found by following the 4 km line down to its intersection with the 2 km level (ordinate) and reading off 39 percent, or by following the 2 km line up to the 4 km level. Finally, the mean average cloudiness at a level was subjectively determined by smoothing both parts of each height line and finding their intersection. The 2-km lines, for

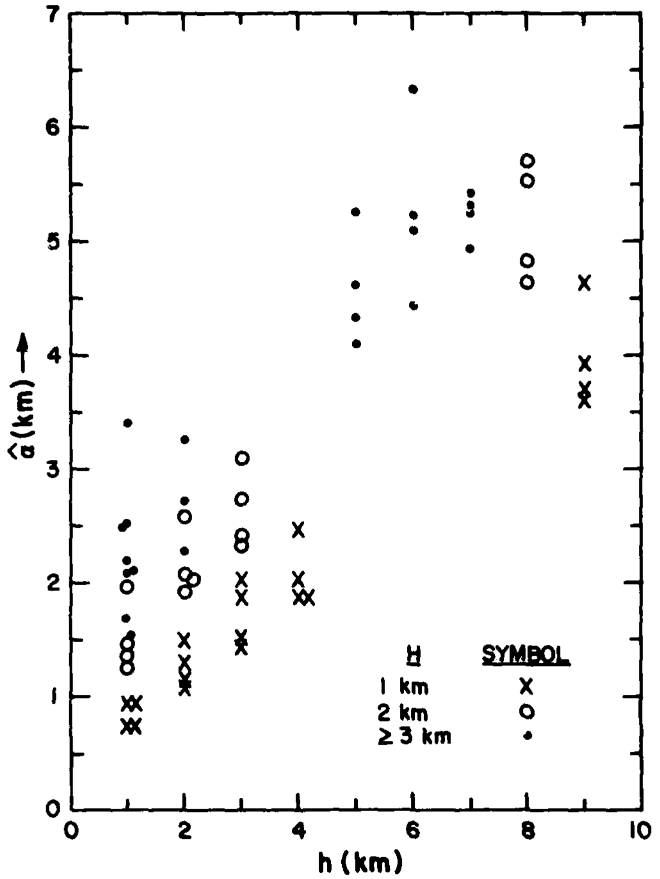

Figure 4. Plot of α, Against Thickness (h) of the Atmospheric Layer. The values of α are computed from the values of deBcry and Moller (1963) for $\bar{P}_H$, $\bar{P}_{H+h}$ and $\bar{p}_h$ from German flights [Eq. (8)]

example, are estimated to intersect at $\bar{P}_H = 0.26$. Or, it is estimated that the cloud presence at 2 km averages 26 percent.

The root mean squared error of the estimates in Figure 5, compared with the deBary and Moller figures is 0.024. The bias is 0.019. For winter and summer, morning and afternoon, the average RMSE was 0.032, and average bias -0.010. However, if the last term in Eq. (8) were dropped, thus making the estimate for $\bar{p}_h$ the same as that adopted by deBary and Moller, and by McCabe, the RMSE would be 0.124 and bias -0.122.

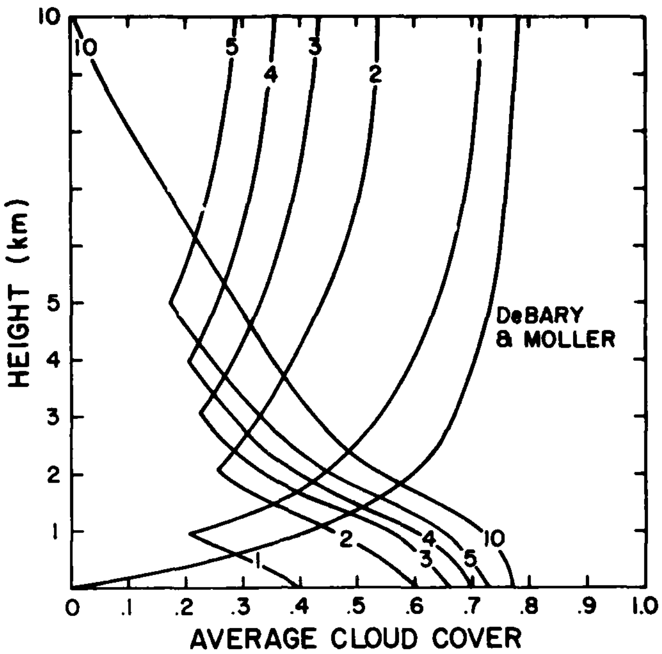

Figure 5. Model Estimates of Average Cloud Cover $\bar{p}_h$ in any Layer h, on Winter Mornings at West German Stations. The thickness h is given by the difference between the height as read on the ordinate scale and the height as marked on the curve

For Bedford, Mass., in January, from 1200 to 1400 LST the estimates ($\bar{P}_H$) of the average cloud cover from the ground up to level (H) given in Table 3, coupled with the values for $\alpha(h, H)$ from Eq. (10), were used in Eq. (8) to give the estimates ($\bar{p}_h$), as shown in Table 4. Since each of these 78 estimates were computed independently, there can be, and there is, some lack of consistency between them. To modify these estimates to make them intrinsically consistent, they were plotted on graph paper (Figures 6a and 6b) for smoothing and correction. To construct Figure 6a, first the 0-line, or the locus of the average sky cover from surface to height (H) was plotted and smoothed. Then the 1000-ft line was plotted and smoothed, making the point on the 1000-ft line at level zero show the same average cover as the 0-line shows at 1000 ft. Then the 500-ft line was drawn, aiming for agreement with the other lines, then the 200-ft line, then the 400-ft line was drawn, and so on, till the graph was completed. Both parts of each curve of one level were extrapolated to cross and thus to give the estimate of the average cloud cover at each level. The same procedure was applied to construct Figure 6b.

Table 4. Estimates of the Average Cloud Cover $\bar{p}_h$, in Layers h, Obtained by Use of Average Sky Cover Frequencies $\bar{P}_H$, Eq. (10) for Parameter Estimate $\hat{\alpha}(h, H)$ and Eq. (8) for $\bar{p}_h$. The information is for Bedford, Mass., in January, from 1200 to 1400 LST. The heights h, H are given in thousands of feet

	(H+h)												
	0.1	0.2	0.3	0.4	0.5	1	2	3	4	5	10	20	all
H													
Sfc:	$\bar{P}_H = 0.011$	0.029	0.045	0.067	0.081	0.171	0.236	0.288	0.337	0.367	0.440	0.524	0.591
0.1		$\bar{p}_h = 0.018$	0.034	0.057	0.071	0.162	0.228	0.280	0.330	0.360	0.434	0.529	0.619
0.2			0.016	0.039	0.054	0.146	0.213	0.267	0.317	0.348	0.423	0.524	0.615
0.3				0.023	0.038	0.132	0.200	0.254	0.306	0.337	0.414	0.519	0.611
0.4					0.015	0.111	0.181	0.237	0.289	0.322	0.400	0.510	0.603
0.5						0.098	0.169	0.225	0.279	0.311	0.392	0.504	0.598
1.0							0.078	0.141	0.200	0.236	0.330	0.456	0.555
2.0								0.068	0.133	0.177	0.291	0.421	0.523
3.0									0.110	0.150	0.255	0.385	0.490
4.0										0.113	0.207	0.341	0.451
5.0											0.176	0.312	0.425
10.0												0.242	0.404
20.0													0.258

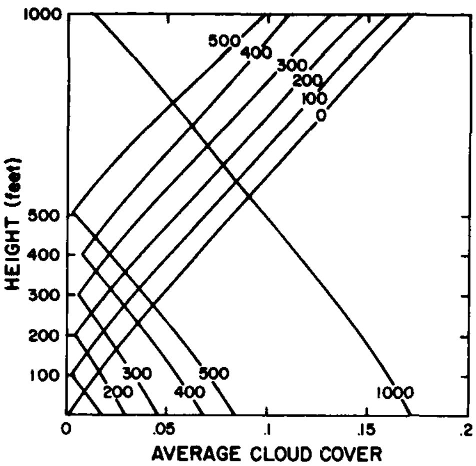

Figure 6a. Model Estimates of Average Cloud Cover p_h in Layers From 0 to 1,000 ft at Bedford, Mass., in January, From 1200 to 1400 LST

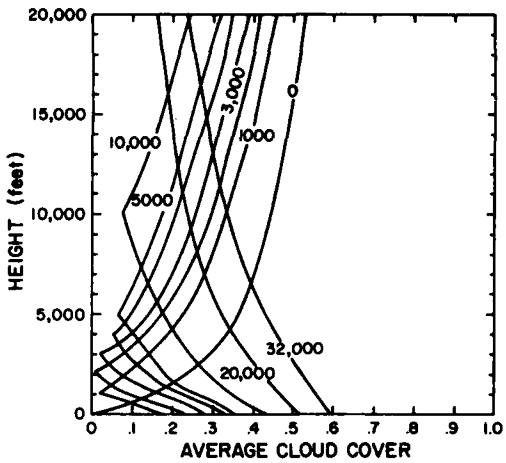

Figure 6b. Model Estimates of Average Cloud Cover p_h in Layers From 0 to 32,000 ft at Bedford, Mass., in January, From 1200 to 1400 LST

Figure 6 (a or b) is similar to the second figure in deBary and Moller (1963).[14] But the deBary figure was constructed with "direct observations within the atmosphere itself." In contrast, Figure 6 was made through use of the RUSSWO data only. This technique makes possible the estimates of cloud cover at, and between, layers with RUSSWO summaries that already exist, without direct observations from aircraft, or other platforms.

One critical aspect in the method of this paper is the procedure for estimating the cloud cover at each level. For each level, the cloud frequency was determined by an extrapolation procedure that was found to be very effective, allowing little room for estimating average cloud cover greater or smaller than shown.

7. PROBABILITY DISTRIBUTIONS OF CLOUD COVER AT, AND BETWEEN, LEVELS

In Section 6 a method for estimating the average cloud cover ($\bar{p}_h$) at, and in layers between, levels has been presented. The goal has been, and still is, identified with the line-of-sight problem: to find the probability of a cloud intersect. But the information on average cloud cover can only be applied to this problem if a model such as Model B is applicable.

To continue further, the previous assumption is involved: Not only is Model B applicable, but the parameter, scale distance, remains the same, for a given

station, time of year, and time of day, for all layers or levels as it is for the total cloud cover from the ground up. Thus, the scale distance for Bedford, Mass., in January, from 1200 to 1400 LST, earlier found to be $r = 2.62$ km for total sky cover, is accepted for any level or layer, and is entered together with the value for area A in Eq. (2) to give the number z in Eq. (1). The latter, in turn, is entered, together with the average cloud cover ($\bar{p}_h$), into Figures 1(0) to 1(10) to find the probability of fractional cloud cover.

The results for Bedford, in the layer between 3000 and 10,000 ft, for an area A of 100 km^2, 2424 km^2 or the sky dome, and 100,000 km^2 are as shown in Table 5. Unlike Table 2, Table 5 shows no corresponding RUSSWO figures, since they do not exist. For the layer between 3000 and 10,000 ft, Table 4 shows an average cloud cover $\bar{p}_h$ of 0.255. As seen in Table 5, there are surprisingly high probabilities of all clear in small areas, and of scattered clouds in even large areas.

Table 5. Probability $p_h(x)$ of Fractional Cloud Cover ($\leq x$) Within the Layer 3000 to 10,000 ft for Bedford, Mass., in January, From 1200 to 1400 LST, for Areas of 100, 2424 and 100,000 km^2 (From Table 4, $\bar{p}_h = 0.255$, for Which $y_h = 0.66$)

Cloud Cover x	Area (km^2) 100, z = 1.93	(Sky Dome) 2424, z = 4.23	100,000, z = 6.92
All clear	0.67	0.50	0.027
≤0.1	0.69	0.60	0.32
≤0.2	0.71	0.65	0.52
≤0.3	0.72	0.69	0.64
≤0.4	0.73	0.73	0.74
≤0.5	0.75	0.76	0.83
≤0.6	0.76	0.79	0.90
≤0.7	0.77	0.815	0.95
≤0.8	0.79	0.85	0.977
≤0.9	0.800	0.88	0.993
Full cover 1.0	0.190	0.075	<0.0001

Figures 7, 8, and 9 are drawn to present the estimates of Table 5, and probabilities at 3000 ft, in addition. All values, to which the curves were plotted, were obtained from Figures 1(0) to 1(10). For example, knowing, from Figure 6(b), that the average cloud presence at 3000 ft is $\bar{p}_3 = 0.03$ for which $y_3 = 1.88$, enter Figure 1(0) with this value of y, which is followed till there is an intersection wit. a selected value of z.

For an area of 100 km^2 (corresponding to $z = 1.93$), p_3 (clear) = 0.953

For an area of 2424 km^2 (corresponding to $z = 4.23$), p_3 (clear) = 0.90

For an area of 100,000 km^2 (corresponding to $z = 6.92$), p_3 (clear) = 0.47

Likewise Figure 1(1) gives p_3 (0.1) = 0.954, 0.93, 0.896 at the same three areal sizes and so on, to give the upper curve of Figures 7, 8, 9.

8. RELEVANCE TO CLOUD-FREE LINE OF SIGHT

To determine the climatic probabilities of a cloud-free line of sight for viewing vertically up or down, procedures leading to Figures 7, 8, and 9 should be relevant. For example, if a cloud-free view from 3000 ft to 10,000 ft is needed within a small area of 100 km^2, Figure 7 shows that the probability of a totally cloud-free view, anywhere in the area, should be 67 percent. But Figure 7 also shows that there should be a cloud-free view of at least half of the 100 km^2 with 75 percent certainty. The probability of full cover is 19 percent.

The problem arises: For what elevation angle is the probability of *CFLOS* given correctly by the observers' cloud cover? It is expected to be 30^o since half of the sky dome is above this angle and half below it. In actual fact, Lund and Shanklin[7] found, from whole-sky photographs, that 10^o elevation CFLOS shows best agreement with the observers' sky cover. The CFLOS frequency was greater with greater elevation angle, but it remained within 2 percent from elevation angles of 50^o to 90^o. Lund and Shanklin had found that some clouds that were reported by ground observers, were missing or undiscernible in the whole-sky photographs. If the clouds had always appeared in the photographs then the best angle of elevation would probably have been close to the expected 30^o.

Synoptically speaking, if an area is partially covered by a cloud deck, for example, by 3/10 cloudiness, within the layer of interest, then the probability of a vertical CFLOS should be 70 percent.

Suppose now, the need is for a horizontal CFLOS at a specified level. There is an average cloud frequency which, for Bedford, Mass., in January, from 1200 to 1400 LST, varies from 0.02 to 0.08 between 1000 ft and 10,000 ft. But there will be instances of no clouds at the specified level for a given area, to occasions of complete cloudiness. For a large-scale example, if an area of 10,000 km^2 at

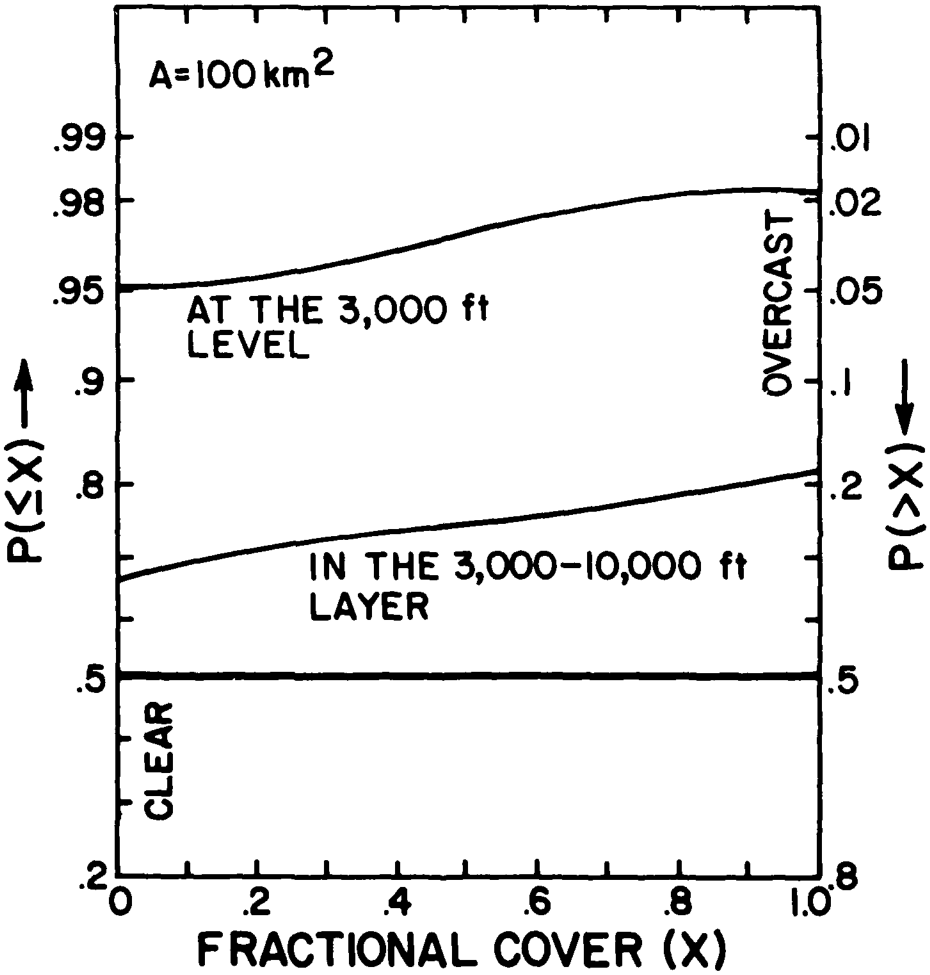

Figure 7. Model B Probability Estimates of Fractional Cloud Cover, From Clear to Overcast, at the 3000-ft Level, and in the 3000- to 10,000-ft Layer, for Bedford, Mass., in January, From 1200 to 1400 LST. Area size is 100 km^2

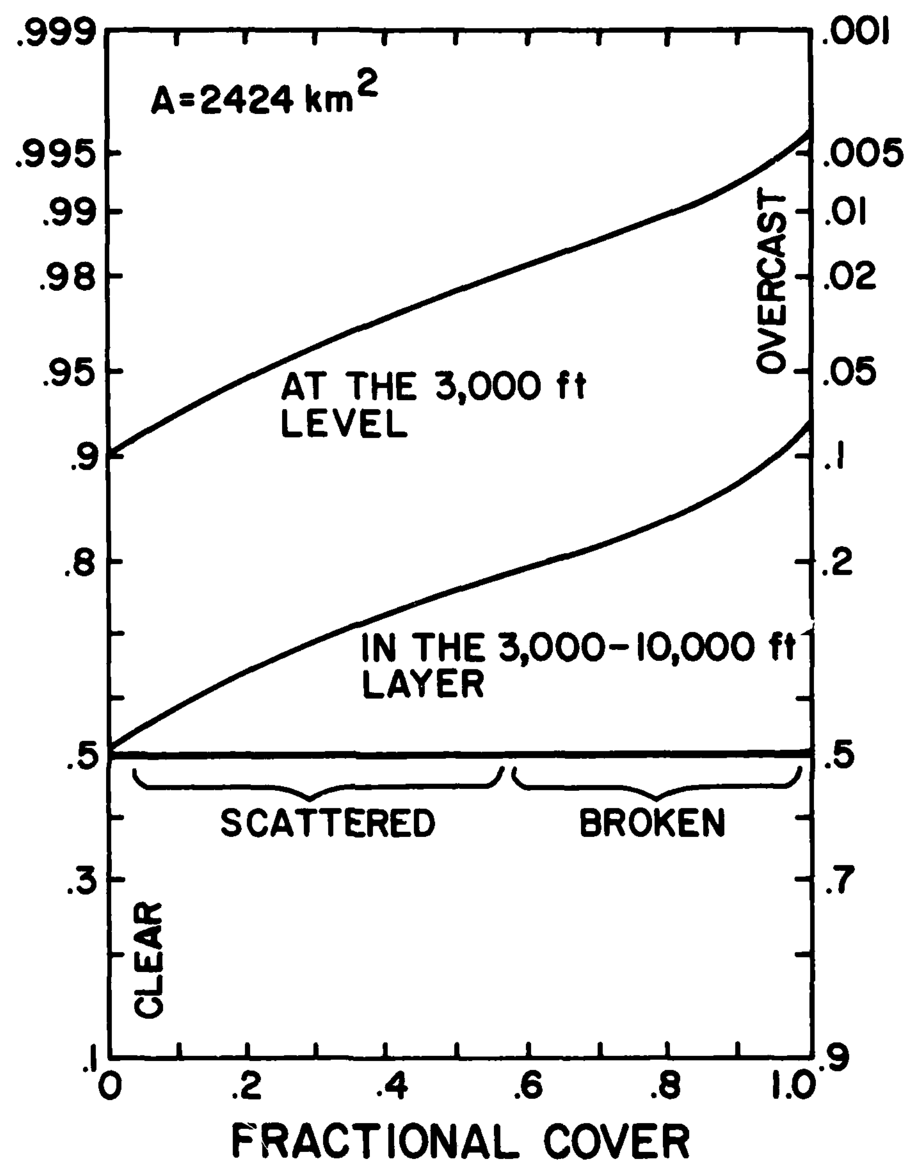

Figure 8. Same as in Figure 7, Except for an Area of 2424 km^2

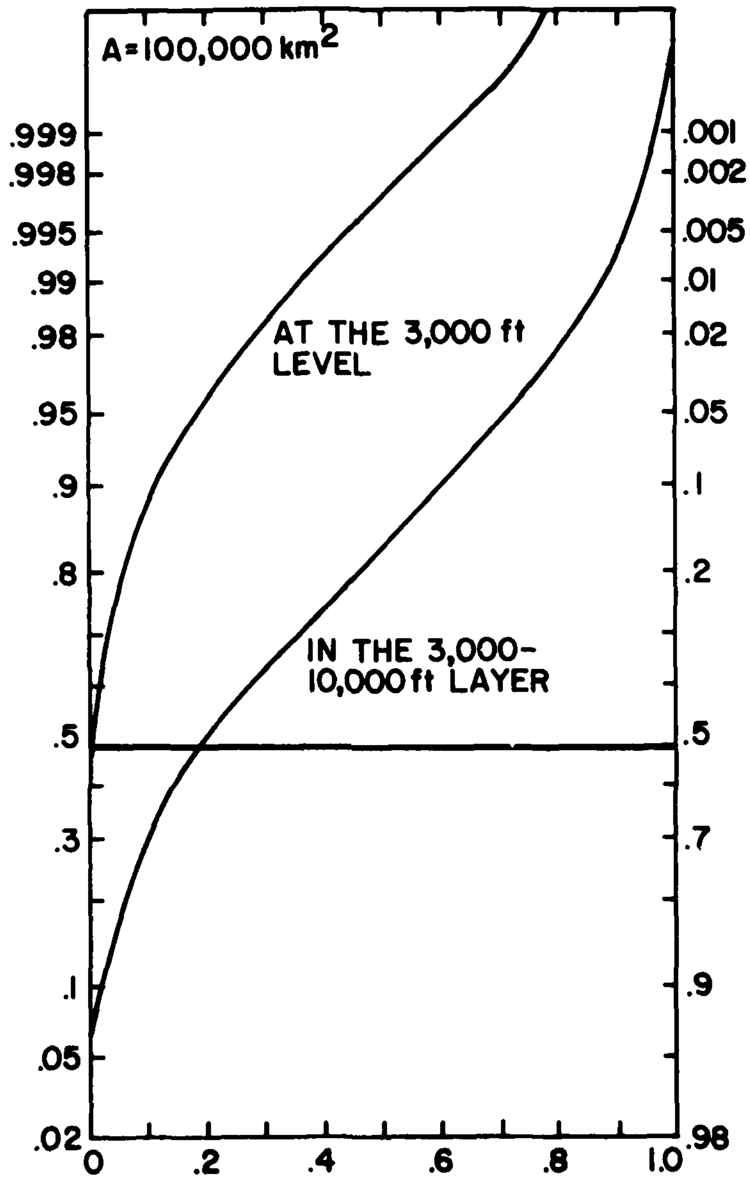

Figure 9. Same as in Figure 7, Except for an Area of 100,000 km^2

the given level is partially occupied by a cloud deck, 3/10 cloudiness, then the not-so-obvious probability of a horizontal CFLOS might be found as follows:

Figure 10 is taken from the background report.[9] A scale of distances has been added along the abscissa. Given r = 2.62 km, then by Eqs. (1) and (2), the distance s' (km) corresponds to

$$z = \ln(s'/2.62)/\ln 2$$

which makes the distance s' of 10 km correspond to z = 1.93, 100 km correspond to z = 5.25, and so on.

If the level of interest is occupied 20 percent by clouds (Y = 0.84) or 80 percent of the horizontal space is cloud-free, then, as Figure 10 reveals, the probability of CFLOS, for a distance of 10 km is 73 percent, for a distance of 100 km it reduces to 56 percent, for a distance of 300 km it reduces to 36 percent, and so on. (This is illustrated by the broken lines on Figure 10.)

9. COMPARISON WITH OTHER MODELS

The topic of this paper is not new. The Air Weather Service has supported several investigations, beginning more than 20 years ago[15,16,17] on the distribution of clouds versus elevation above ground level. Taylor's title offered considerable promise but unfortunately the paper was not published. The papers of deBary and McCabe have been useful for this present exercise.

Among the contributions of this present paper is the use made of the RUSSWO information, without recourse to rare inflight information on the cloud presence at levels above the ground. Also, this paper offers a method of estimating the probability distribution of cloud cover within layers of the atmosphere at selected levels.

There have been other papers written to present models of the probability distribution of sky cover. Falls[18,19] used the Beta distribution for sky cover upon

16. Solomon, I. (1961) Estimates of Altitudes with Specified Probabilities of Being Above All Clouds, Technical Report 159, Air Weather Service, USAF.
17. Taylor, J.H. (1958) Frequencies of Various Cloud Amounts by Altitude, Climatic Center, AWS, USAF (unpublished paper).
18. Falls, L.W. (1973) The Beta Distribution: A Statistical Model for World Cloud Cover, NASA Technical Memorandum No. 64714, Marshall Space Flight Center, Alabama.
19. Falls, L.W. (1974) The Beta distribution: a statistical model for world cloud cover, J. Geophys. Res. 79:1261-1264.

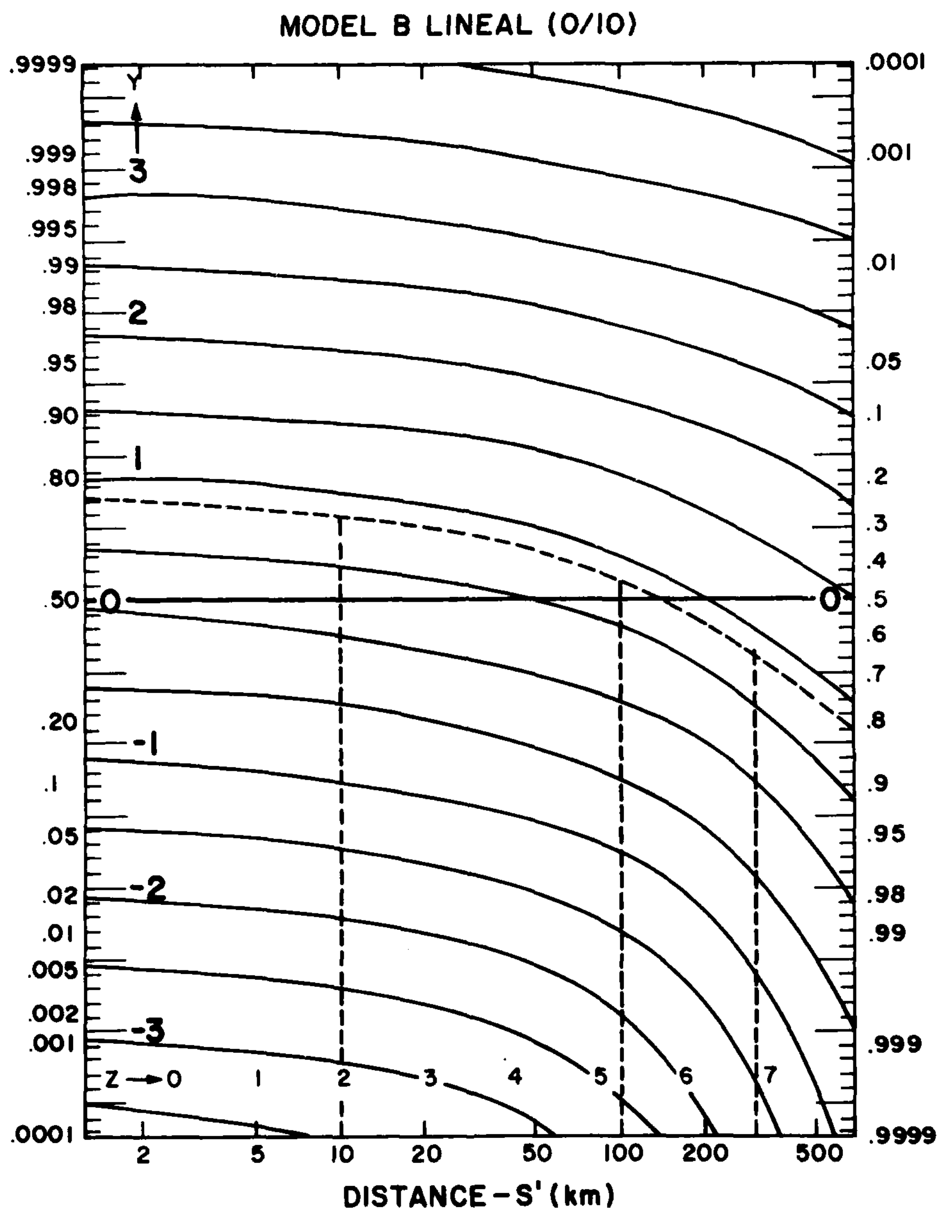

Figure 10. Model B Probability Estimates of Zero Cloud Cover (x = 0/10) Along a Line. Distance s' is in km, for Bedford, Mass., in January, From 1200 to 1400 LST (r = 2.62 km)

the merits of which Henderson-Sellers et al[20] have enlarged. Falls' model has been adopted in several other studies, in particular to worldwide coverage as described by Bean and Somerville.[21] Somerville[22] also has offered an alternative model, based on Johnson curves. But both the Beta and Johnson algorithms suffer from a failure theoretically to yield the sizeable estimates of (strictly) clear and overcast. Moreover, it remains unclear how they can be generalized to model the cloud cover over terrestrial areas that are smaller or larger than the observer's "sky dome." They are mentioned here, however, as alternatives to the modeling in this report. They are simpler and more compact.

Another point might be made with respect to alternative models. What are the parameters? How many? Both the Beta and Johnson curves have two parameters, but their physical meaning is not clear. In the model used in this report, one of the two parameters is the mean cloud cover. Mapping of this parameter, just by itself, will provide useful information. The second parameter, scale distance, or the distance over which the correlation of cloud cover is 0.99 can also be advantageously mapped, to provide information on the horizontal persistence of the cloud cover.

10. CONCLUDING REMARKS

The probability estimates of cloud cover at specific levels and in layers between levels have been found by modeling. A procedure has been outlined for applying Model B, previously developed and published in the Journal of Applied Meteorology. The procedure begins with two requisite parameters, average sky cover and scale distance.

There have been several assumptions made, which can be restated as follows:

(1) The horizontal persistence, or variability, of sky cover is describable with sufficient degree of accuracy by Model B. Scale distance is an adequate measure of this persistence, acceptably constant within the constraint of geographic location, time of year and time of day.

(2) The sky dome, as a ground observer sees it, has a radius of 15 nm or 27.8 km.

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20. Henderson-Sellers, A., Hughes, N.A., and Wilson, M. (1981) Cloud cover archiving on a global scale: a discussion of principles, Bull. of the Amer. Meteorol. Soc. 62:1300-1307.

21. Bean, S.J., and Somerville, P.N. (1981) Some new world-wide cloud-cover models, J. Appl. Meteorol. 20:223-228.

22. Somerville, Paul N. (1978) Some Models for Sky Cover, Scientific Report No. 2 Contract No. F19628-77-C-0080. Florida Technological University, Orlando, Florida, AFGL-TR-78-0219, ADA 062650.

(3) The mean sky cover, or the average cloud cover, as seen by the observer, is the same as his line-of-sight probability of a cloud intersect overhead. We have assumed that this probability is the same for any elevation angle and for any azimuth.

(4) For a given station, time of year, and time of day, the scale distance will serve, unchanged, as the parameter that defines persistence, for clouds at any level or clouds between any two levels. This could be the worst assumption, and should be considered subject to modification with experience. So far, it has been used with a good degree of success, as seen in Figure 5, in which the estimated average cloud cover, at the five levels, 1 to 5 km, and in layers, was compared with determinations by aircraft over Germany, 1936-1940. The bias is quite small, and the root mean square error less than 1/10 of the cloud cover.

(5) The probability of a cloud at a high level occurring directly above a cloud at a lower level is greater than the unconditional probability of cloudiness at the higher level. A parameter α has been introduced that is a measure of the persistence from one level to the next. As the atmospheric layer thickens, the conditional probability of clouds in the layer above the lower clouds decreases toward the unconditional probability.

As a tool, Model B is not yet equipped with analytical algorithms for quick answers by computer. Instead, methods by graphical solutions have been presented, requiring the use of Figures 1(0) to 1(10) and Figure 10, together with Eqs. (1) and (2) or (4). There is an ongoing effort to adopt Figures 1 and 10 to computer usage through curve-fitting methods. The results of this effort will greatly expedite the use of the model presented in this paper. To find the average cloud cover in layers a value must be stipulated for the parameter (α). This parameter was found to vary with layer height and thickness. Its formula was obtained to fit limited data from Germany. The model, therefore, is most likely to provide best estimates at mid-latitude continental locations, and provides more speculative estimates for Arctic or tropical locations. Eq. (10) is assumed applicable everywhere, for all seasons and times of day. Eq. (8) is then used for the cloud cover averages in the layers.

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